

VIS³COS: III. nature and nurture in galaxy structure and morphology

Ana Paulino-Afonso^{1,2,3,*}, David Sobral³, Behnam Darvish⁴, Bruno Ribeiro⁵, Arjen van der Wel^{6,7}, John Stott³, Fernando Buitrago^{1,2}, Philip Best⁸, Andra Stroe⁹, and Jessica E. M. Craig³

- ¹ Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa, OAL, Tapada da Ajuda, PT1349-018 Lisboa, Portugal
² Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Edifício C8, Campo Grande, PT1749-016 Lisboa, Portugal
³ Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK
⁴ Cahill Center for Astrophysics, California Institute of Technology, 1216 East California Boulevard, Pasadena, CA 91125, USA
⁵ Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
⁶ Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
⁷ Sterrenkundig Observatorium, Universiteit Gent, Krijgslaan 281 S9, B-9000 Gent, Belgium
⁸ Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
⁹ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We study the impact of local density and stellar mass on the structure and morphology of ~ 500 quiescent and star-forming galaxies from the VIMOS Spectroscopic Survey of a Superstructure in COSMOS (VIS³COS). We perform bulge-to-disk decomposition of the surface brightness profiles and find $\sim 41 \pm 3\%$ of $> 10^{10} M_{\odot}$ galaxies to be best fitted with two components. We complement our analysis with non-parametric morphological measurements and qualitative visual classifications. We find that both galaxy structure and morphology depend on stellar mass and environment for our sample as a whole. We only find an impact of the environment on galaxy sizes for galaxies more massive than $10^{11} M_{\odot}$. We find higher Sérsic indices (n) and bulge-to-total ratios (B/T) in high-density regions when compared to low-density counterparts at similar stellar masses. We also find that higher stellar mass galaxies have steeper light profiles (high n , B/T) compared to lower stellar mass galaxies. Using visual classifications, we find a morphology-density relation at $z \sim 0.84$ for galaxies more massive than $10^{10} M_{\odot}$, with elliptical galaxies being dominant at high-density regions and disk galaxies more common in low-density regions. However, when splitting the sample into colour-colour selected star-forming and quiescent sub-populations, there are no statistically significant differences between low- and high-density regions. We find that quiescent galaxies are smaller, have higher Sérsic indices (for single profiles, around $n \sim 4$), and higher bulge-to-total light ratio (for decomposed profiles, around $B/T \sim 0.5$) when compared to star-forming counterparts ($n \sim 1$ and $B/T \sim 0.3$, for single and double profiles, respectively). We confirm these trends with non-parametric quantities, finding quiescent galaxies to be smoother (lower asymmetry, lower M_{20}) and having most of their light over smaller areas (higher concentration and Gini coefficient) than star-forming galaxies. Overall, we find that the dependence of structure and morphology on stellar mass are stronger than with local density and these relations are strongly correlated with the quenching fraction. The change in average structure or morphology corresponds to a change in the relative fractions of blue disk-like galaxies and red elliptical galaxies with stellar mass and environment. We hypothesize that the processes responsible for the quenching of star-formation must also affect the galaxy morphology on similar timescales.

Key words. galaxies: evolution – galaxies: high-redshift – galaxies: structure – large-scale structure of Universe

1. Introduction

In a Λ CDM Universe, galaxies form in dark matter halos when baryonic matter cools and collapses (e.g. White & Rees 1978). This provides a hierarchical scenario where massive objects are formed through mergers of smaller entities. However, the exact details of galaxy formation and evolution still elude our current understanding. The hierarchical nature of structure formation naturally produces different pathways of galaxy evolution based on the local

density, as denser regions have a higher probability of interactions which influence galaxy properties.

By studying samples of galaxies across different regions Dressler (1980) found a clear dichotomy in galaxy morphology when looking at low- (hereafter referred as field) and high-density (cluster) environments in the local Universe (see also e.g. Guzzo et al. 1997; Goto et al. 2003; Bamford et al. 2009; Skibba et al. 2009; Fasano et al. 2015). Galaxies in field environments are on average bluer, more star-forming, and disk-like while galaxies in cluster environments are older, redder, less star-forming, and elliptical

* E-mail: aafonso@oal.ul.pt

(e.g. Dressler 1984; Gómez et al. 2003; Kauffmann et al. 2004; Boselli & Gavazzi 2006; Blanton & Moustakas 2009; Deeley et al. 2017).

Changes in galaxy morphology with environment are not only found in the local Universe but also at intermediate- ($z \lesssim 1$, e.g. Dressler et al. 1997; Treu et al. 2003; Postman et al. 2005; Capak et al. 2007; van der Wel et al. 2007; Tasca et al. 2009; Kovač et al. 2010; Nantais et al. 2013; Allen et al. 2016; Krywult et al. 2017; Kuchner et al. 2017) and high-redshifts ($z \sim 1 - 2$, e.g. Grützbauch et al. 2011; Bassett et al. 2013; Strazzullo et al. 2013; Allen et al. 2015). There are some hints of the environmental impact on galaxy sizes at $z \sim 1 - 2$ (e.g. Papovich et al. 2012; Delaye et al. 2014; Mei et al. 2015) but that is not seen in the local Universe (e.g. Huertas-Company et al. 2013b; Kelkar et al. 2015) nor in protocluster environments (see e.g. Peter et al. 2007). By measuring sizes of field and cluster galaxies, several studies find quiescent galaxies to show little difference in their sizes at fixed stellar mass at $0 < z < 2$ (e.g. Huertas-Company et al. 2013a,b; Cebrián & Trujillo 2014; Newman et al. 2014; Kelkar et al. 2015; Allen et al. 2015, 2016; Saracco et al. 2017) while others find evidence for larger quiescent galaxies in cluster environments (e.g. Papovich et al. 2012; Bassett et al. 2013; Lani et al. 2013; Strazzullo et al. 2013; Delaye et al. 2014; Yoon et al. 2017). For star-forming galaxies, there is also not a clear trend, with some studies finding little difference among cluster and field galaxies (e.g. Lani et al. 2013; Kelkar et al. 2015) and others finding larger star-forming galaxies in cluster environments (e.g. Cebrián & Trujillo 2014; Tran et al. 2017, locally and at $z \sim 2$, respectively). Studies by Allen et al. (2015, 2016) show that star-forming galaxies are larger in cluster environments at $z \sim 1$ and smaller at $z \sim 2$ than their field counterparts. This differential evolution in galaxy sizes hints at different paths for galaxy growth in different environments.

Differences among star-forming and quiescent galaxies can evolve through the morphological transformation of blue star-forming disk-dominated galaxies to redder quiescent and bulge-dominated (or pure elliptical) galaxies (e.g. through minor and major mergers, De Lucia et al. 2011; Shankar et al. 2014). In terms of galaxy light profiles, studies find that galaxies residing in the cluster environments might be more bulge-dominated (e.g. Goto et al. 2003; Poggi et al. 2008; Skibba et al. 2012; Bluck et al. 2014). By quantifying the light distribution in galaxies with Sérsic (1968) profiles, Allen et al. (2016) find that in and around a $z \sim 0.92$ cluster, star-forming galaxies are more likely to have higher Sérsic indices than their field counterparts but report no difference among quiescent galaxies. At $z \sim 1.6$, Bassett et al. (2013) find no differences between field and cluster star-forming galaxies but report shallower profiles (lower Sérsic index) for quiescent galaxies in a cluster environment. When comparing star-forming and quiescent galaxies, the latter have higher Sérsic indices due to a prevalence of ellipticals and/or a dominant bulge in the redder population (e.g. Bassett et al. 2013; Morishita et al. 2014; Cerulo et al. 2017). High Sérsic index galaxies are also the types of galaxies that are more common in higher density regions out to $z \sim 1$ (e.g. Dressler et al. 1997; Treu et al. 2003; Postman et al. 2005; Capak et al. 2007; van der Wel et al. 2007; Tasca et al. 2009; Nantais et al. 2013).

When performing more detailed bulge-to-disc decomposition of the light profiles, studies find a rise in the bulge-

dominated fraction since $z \sim 3$ (e.g. Bruce et al. 2014a; Tasca et al. 2014; Margalef-Bentabol et al. 2016). In the local Universe, there are hints that the build-up of galactic bulges is happening in higher density environments (e.g. Lackner & Gunn 2013). At intermediate redshifts ($z \sim 0.4 - 0.8$), Grossi et al. (2018) found that for a sample of $H\alpha$ -selected galaxies, they tend to have more prominent bulges at higher density environments. However, we lack observations of the environmental dependence of the bulge prevalence at these redshifts for a continuum-selected sample.

The morphology-colour-density relation suggests that there is at least one physical mechanism that changes galaxy morphology as well as acts in the suppression of the star formation activity. Several processes have been proposed that include gas removal from the disk (e.g. Larson et al. 1980), ram pressure stripping from the intra-cluster medium (e.g. Gunn & Gott 1972; Abramson et al. 2016), galaxy harassment through tidal forces (e.g. Moore et al. 1996), and eventual galaxy mergers (e.g. Burke & Collins 2013). At the same time, there is a typical stellar mass in which quenching is effective due to overdense environments (e.g. Peng et al. 2010b, 2012).

In this manuscript we study a sample of spectroscopically confirmed sources in and around a superstructure at $z \sim 0.84$ in the COSMOS field (Scoville et al. 2007) for which we have available high-resolution spectra covering [OII], the 4000Å break, and $H\delta$ (Paulino-Afonso et al. 2018b, hereafter PA18). We aim to investigate the relationship between galaxy morphology and stellar mass and environment, and link that to the star formation to shed some light on the processes that are most likely to be responsible for morphological transformations.

This manuscript is organized as follows: in Section 2 we briefly explain the VIS³COS survey, on which our manuscript is based. Section 3 details the morphological measurements on the sources used in this article. In Sections 4 and 5 we highlight some of the key results of our study in terms of galaxy stellar mass, environment, and star formation. In Section 6 we discuss our findings within the context of current galaxy formation and evolution literature. In Section 7 we summarize our results. We use AB magnitudes (Oke & Gunn 1983), a Chabrier (Chabrier 2003) initial mass function (IMF), and assume a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. The physical scale at the redshift of the superstructure ($z \sim 0.84$) is $7.63 \text{ kpc}''$.

2. Sample and data

2.1. The VIS³COS survey

The VIMOS Spectroscopic Survey of a Superstructure in the COSMOS field (VIS³COS, PA18) is based on an observing programme with the VIMOS¹ instrument mounted at VLT to obtain high-resolution spectroscopy down to the continuum level for galaxies in and around a large structure at $z \sim 0.84$ in the COSMOS field. The observations span an area of $21' \times 31'$ ($9.6 \times 14.1 \text{ Mpc}$) with an overdensity of $H\alpha$ emitters (Sobral et al. 2011; Darvish et al. 2014) and three confirmed X-ray clusters (Finoguenov et al. 2007). This is the third manuscript from this survey and the full descrip-

¹ Programmes 086.A-0895, 088.A-0550, and 090.A-0401

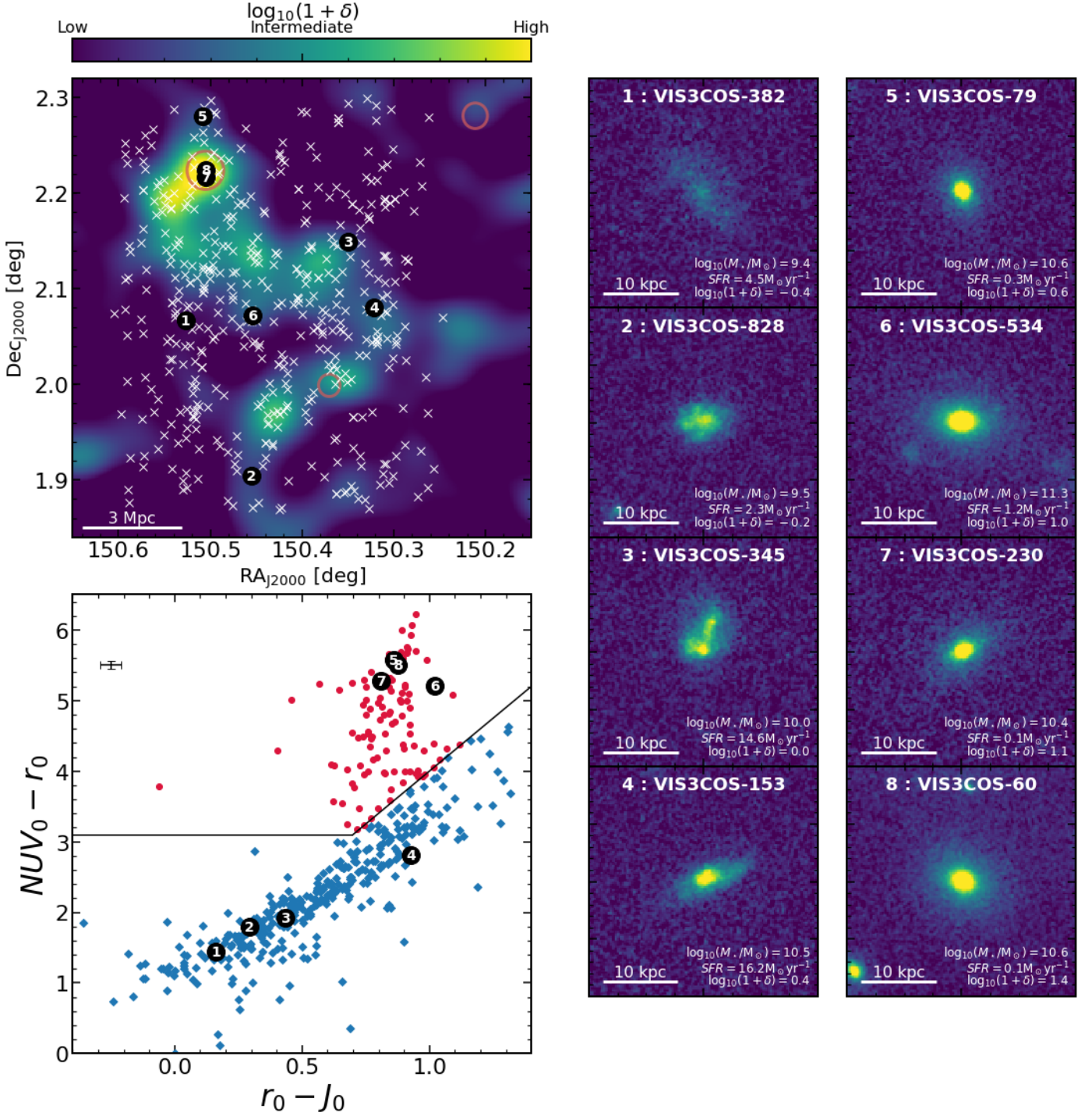


Fig. 1. Top left: an overview of the VIS³COS survey showing the galaxy overdensity and targeted galaxies at $0.8 < z < 0.9$ with spectroscopic redshifts (white crosses) along with the location of known X-ray clusters (empty red circles, [Finoguenov et al. 2007](#)). Bottom left: the NUV-r-J diagram (derived using [Laigle et al. 2016](#) photometry) for galaxies in our survey, with the separation between quiescent (red circles) and star-forming (blue diamonds) as defined by [Ilbert et al. \(2013\)](#) shown as a solid line. We show the average error on each colour as a black cross. Right panels: examples of HST/ACS F814W 4''x4'' rest-frame *B*-band images of eight of our sources with individual information on stellar mass, SFR, and local overdensity in each panel. We highlight the position of these eight galaxies with large numbered black circles in the left panels.

tion of the data and derived physical quantities is presented in [PA18](#). We summarize here the relevant information.

We targeted galaxies from the [Ilbert et al. \(2009\)](#) catalogue which had $0.6 < z_{\text{phot},1} < 1.0$ (with $z_{\text{phot},1}$ being either the upper or lower 99% confidence interval limit for each source) and being brighter than $i_{\text{AB}} < 23$. We used the

VIMOS High-Resolution red grism (with the GG475 filter, $R \sim 2500$) with six overlapping VIMOS pointings to mitigate selection effects on higher density regions. Our choice of grism covers the 3400-4600Å rest-frame region at the redshift of the superstructure, which has interesting spec-

tral features such as [OII] $\lambda 3726, \lambda 3729$ (partially resolved doublet), the 4000 Å break, and H δ .

The spectroscopic redshifts were computed from the extracted 1D spectra using SPECPRO (Masters & Capak 2011). The redshift determination is based on a set of prominent spectral features: [OII], H+K absorption, G-band, some Fe lines, and H δ . We obtained successful spectroscopic redshifts for 696 galaxies, of which 490 are within our primary redshift selection ($0.8 < z < 0.9$, PA18).

With the knowledge of the spectroscopic redshift, we can improve on existing physical quantity measurements. We obtained stellar masses and star formation rates (SFRs) from running MAGPHYS (da Cunha et al. 2008) with spectral models constructed from the stellar libraries by Bruzual & Charlot (2003) on the set of photometric bands from near-UV to near-IR from the COSMOS2015 catalogue (Laigle et al. 2016). The dust is modelled based on the Charlot & Fall (2000) prescription.

We use a measurement of local overdensity based on the cosmic density field value at the 3D position of each target. We use the density estimation of Darvish et al. (2015, 2017) which is constructed from a K_s magnitude-limited sample based on the Ilbert et al. (2013) photometric redshift catalogue. The density field was computed for the $\sim 1.8 \text{ deg}^2$ area in COSMOS over a large redshift interval ($0.05 < z_{\text{phot}} < 3.2$) with an adaptive smooth kernel with a characteristic size of 0.5 Mpc (Darvish et al. 2015, 2017). In this manuscript, we define overdensity as $1 + \delta = \Sigma / \Sigma_{\text{median}}$, with Σ_{median} being the median of the density field at the redshift of the galaxy. For a detailed description of the density estimation method, we refer the reader to Darvish et al. (2015, 2017).

The final sample we study in this manuscript is selected to be at $0.8 < z < 0.9$ (matching our target selection) and has a total of 490 galaxies spanning a large diversity of stellar masses (with 295 above our selection limit $\sim 10^{10} M_{\odot}$, PA18) and environments across ~ 10 Mpc. We show an overview of the main properties of the sample and survey in Fig. 1. We also note that we are probing both star-forming (371 galaxies) and quiescent (119 galaxies) populations within this region (defined from the NUV-r-J diagram, see e.g. Ilbert et al. 2013 and Fig. 1).

2.2. Imaging data

Since this structure is part of the COSMOS field, we base our morphological measurements on data from the HST/ACS F814W COSMOS survey (Koekemoer et al. 2007; Scoville et al. 2007). These images have a typical PSF FWHM of $\sim 0.09''$, a pixel scale of $0.03''/\text{pixel}$, and a limiting point-source depth $\text{AB}(\text{F814W}) = 27.2$ (5σ). At the redshift of the superstructure, these images probe the rest-frame B -band galaxy morphology with sub-kpc resolution.

We use $10'' \times 10''$ cut-outs (corresponding to square images with a ~ 76 kpc side at the redshift of the superstructure) centred on the target position. To account for the PSF, we use the HST/ACS PSF profiles that were created with TINYTIM (Krist 1995) models and described by Rhodes et al. (2006, 2007; see also Paulino-Afonso et al. 2017).

3. Morphological characterization of the sample

Quantitative morphological analysis has complemented visual classification of images in the past decades. There are two main groups of morphological characterization: parametric modelling of the surface brightness profiles (e.g. de Vaucouleurs 1959; Sérsic 1968; Simard 1998; Trujillo et al. 2001; de Souza et al. 2004; Peng et al. 2002, 2010a; Simard et al. 2011) and non-parametric quantitative morphology (e.g. Abraham et al. 1994, 2003; Bershadsky et al. 2000; Conselice et al. 2000; Conselice 2003; Papovich et al. 2003; Lotz et al. 2004; Blakeslee et al. 2006; Law et al. 2007; Freeman et al. 2013; Pawlik et al. 2016). Each method has its own strengths and drawbacks and the choice is usually related to a particular scientific question. Parametric models are more effective in getting a description of the light profile to get galaxy size estimates (e.g. Blanton et al. 2003; Trujillo et al. 2007; Buitrago et al. 2008; Wuyts et al. 2011; van der Wel et al. 2014) and to perform bulge-to-disk decomposition (e.g. de Souza et al. 2004; Tasca et al. 2009; Simard et al. 2011; Meert et al. 2013; Bruce et al. 2014a,b; Lang et al. 2014; Margalef-Bentabol et al. 2016; Gao & Ho 2017; Dimauro et al. 2018). Non-parametric methods are often used to identify irregularities in galaxies as signatures of past or ongoing mergers (e.g. Lotz et al. 2008; Conselice et al. 2009; Bluck et al. 2012; Freeman et al. 2013; Pawlik et al. 2016). Since we are interested in the process of morphology transformation from low to dense environments, we use a combination of both methods along with visual classification to have a complete perspective on the impact of environment on galaxy morphology.

3.1. Parametric modelling of galaxies

To have an estimate of the structural parameters of galaxies we fit Sérsic (1968) profiles to all objects in our catalogue using GALFIT (Peng et al. 2002, 2010a). We also use SEXTRACTOR (Bertin & Arnouts 1996) to provide initial guesses for each galaxy model and to produce binary images to mask all nearby objects that might affect the fit. This method follows closely the procedures defined in Paulino-Afonso et al. (2017) and Paulino-Afonso et al. (2018a). We fit all galaxies with two models: a single Sérsic profile and a combination of an exponential disk with a central Sérsic profile to account for the existence of a bulge+disk systems. We chose to do so since we are dealing with a population of galaxies where sub-structures can be resolved (see e.g. Tasca et al. 2009). We use the Bayesian Information criterion (BIC, e.g. Kelvin 2012; Bruce et al. 2014b) to select which model best fits each galaxy (see Appendix A.1 for more details).

3.2. Non-parametric quantitative morphology

We implement two sets of non-parametric indices that allow us to get additional structural indicators without the need to assume any model: the CAS system (Conselice et al. 2000; Conselice 2003, see also Abraham et al. 1994 and Bershadsky et al. 2000) and the G- M_{20} system (Lotz et al. 2004, see also Abraham et al. 2003). The two latter indices are computed over the segmentation map of the galaxy, which is computed as the group of a minimum of 10 connected pixels above 3σ that are closest to the object coordinates. These indices are commonly used to detect disturbed galaxy light

profiles associated with on-going galaxy mergers (e.g. Conselice 2003; Lotz et al. 2004, 2008; Conselice et al. 2009). For more details on each index see Appendix A.2.

3.3. Visual classification

The classification of galaxies into different categories has been done extensively over a century (e.g. Hubble 1926, 1930; de Vaucouleurs 1959; van den Bergh 1976; Nair & Abraham 2010; Baillard et al. 2011; Buitrago et al. 2013; Buta et al. 2015; Kartaltepe et al. 2015). This is a time-consuming task if one wishes to carry it out on large samples and has the problem of not being reproducible and subject to individual bias. More recently, the citizen science project Galaxy Zoo (Lintott et al. 2008) has combined results from more than 200,000 classifiers to produce a reliable catalogue of visual classifications (Lintott et al. 2011; Willett et al. 2013, 2017). In this manuscript, we use the data release of Galaxy Zoo containing the classifications for Hubble Space Telescope images, fully described by Willett et al. (2017). Out of 490 galaxies within our sample at $0.8 < z < 0.9$ we find a match for 447 objects. To map the classifications from Galaxy Zoo to the three classical morphologies (elliptical, disk, or irregular, see e.g. Paulino-Afonso et al. 2018a), we use the first and second tier questions (Willett et al. 2017, Figure 4). We use the recommended fractions (with corrections for classification bias) and establish the following criteria (for more details see Appendix A.3):

- Elliptical - $f_{\text{smooth}} > 0.50$ and $f_{\text{odd}} < 0.5$ and $f_{\text{cigar-shaped}} < 0.5$ and $f_{\text{features}} < 0.23$ (to impose mutually exclusive classification);
- Disk - $f_{\text{features}} > 0.23^2$, and $f_{\text{clumpy}} < 0.5$ and $f_{\text{odd}} < 0.5$ or $f_{\text{smooth}} > 0.50$ and $f_{\text{odd}} < 0.5$ and $f_{\text{cigar-shaped}} > 0.5$;
- Irregular - $f_{\text{odd}} > 0.5$ or $f_{\text{features}} > 0.23$ and $f_{\text{clumpy}} > 0.5$.

4. Galaxy structure/morphology dependence on stellar mass and environment

We group galaxies in three different samples based on the local density to trace objects which should be representative of field ($\log_{10}(1 + \delta) \leq 0.1$), intermediate-density and filaments ($0.1 < \log_{10}(1 + \delta) \leq 0.6$), and cluster galaxies ($\log_{10}(1 + \delta) > 0.6$) based on the relation of the cosmic web environment with overdensity (see PA18). Unless stated otherwise, the horizontal error bars delimit the bins and the vertical error bars show the value of the 16th (lower uncertainty) and 84th (upper uncertainty) percentiles of the distribution for each bin normalized by the bin size as $[P_{16\%}, P_{84\%}] / \sqrt{N_{\text{gal}}}$. We also compute the Spearman (1904) correlation coefficient, ρ , and the probability of the relation being random for all of the relations explored in this manuscript and show them in the individual panels of each figure.

Of the 490 galaxies at $0.8 < z < 0.9$ we have successfully fit their light profiles with either a one- or two-component model to 470 (96%) of them. The remaining 20 galaxies failed to converge. Following Section 3.1 we find a total of 173 galaxies for which their best fit is a two-component model. Considering only galaxies with

stellar masses greater than $10^{10} M_{\odot}$, we find a fraction of $\sim 41 \pm 3\%$ of two-component systems. This is in agreement with the reported two-component model fraction of $35 \pm 6\%$ at $z \sim 1$ by Margalef-Bentabol et al. (2016) for a sample of $\log_{10}(M_{\star}/M_{\odot}) > 10$ galaxies.

4.1. Parametric quantities

To compare the morphology of galaxies across different stellar masses and environments in a consistent way, we use as a size estimate the effective radius of the single Sérsic model for each galaxy. We also do the same when showing Sérsic indices. For the bulge-to-total ratio (B/T), we use the value from the two-component model for galaxies, which has a statistically better fit (see App. A.1). For galaxies that are best fit with a single Sérsic profile we assign a value of $B/T=0$ if $n < 2.5$ and $B/T=1$ if $n \geq 2.5$ (see e.g. Shen et al. 2003; Barden et al. 2005; Cebrián & Trujillo 2014; Lange et al. 2015; Kuchner et al. 2017 regarding the n threshold). We note that using a different threshold for the separation (e.g. $n = 2$, Ravindranath et al. 2004) does not qualitatively change our results. An alternative would be to introduce an estimate of B/T (between 0 and 1) based on the value of the best fit Sérsic index of each galaxy. However, doing so would introduce the underlying correlation of stellar mass and local density with the Sérsic index on all relations for B/T , making it more difficult to interpret the results independently.

We show in Fig. 2 the dependence of galaxy sizes, Sérsic indices, and B/T on the environment for galaxies more massive than $10^{10} M_{\odot}$. We find that for a given stellar mass range there is no significant change in galaxy size (for the low- and intermediate-mass bins) and the correlation with local density is weak ($\rho < 0.15$). For the highest stellar mass bin we find that in the higher density regions there is a lack of small galaxies ($\lesssim 4\text{kpc}$) which drives the median value towards $\sim 40\%$ larger sizes, but the correlation with density is weak ($\rho = 0.12$). The larger sizes of galaxies in the densest regions cannot be explained alone by changes in the mean stellar mass for each density bin. The most likely scenario is the growth through galaxy mergers driving this difference (see e.g. Papovich et al. 2012; Cappellari 2013; Yoon et al. 2017 for local early-type galaxies, which are the dominant population in the high stellar mass bin in our study). On the other hand, we find that more massive galaxies are larger, as expected from the underlying stellar mass-size relation (see e.g. Franx et al. 2008; van der Wel et al. 2014; Morishita et al. 2014; Paulino-Afonso et al. 2017; Mowla et al. 2019).

The median Sérsic index increases with stellar mass with more massive galaxies having steeper light profiles (higher values of n). We also find that for a given stellar mass bin, there is an increase in n for denser environments, more specifically, when comparing the densest with the lowest regions probed with VIS³COS. The lack of disk-like galaxies ($n \lesssim 2.5$) at all stellar masses in high-density regions is especially noteworthy. We find that the correlation with local density is stronger for the higher stellar mass bin in our sample ($\rho = 0.31$) and that for the lower stellar mass bin the correlation is not significant ($\rho = 0.05$).

The trends of B/T with stellar mass and environment are seen in Fig. 2 with strong differences found among galaxies with different stellar masses at a fixed local overdensity. We also find a significant trend with galaxies in denser envi-

² As suggested by Willett et al. (2017, see Table 11) when considering fractions on the second tier of questions.

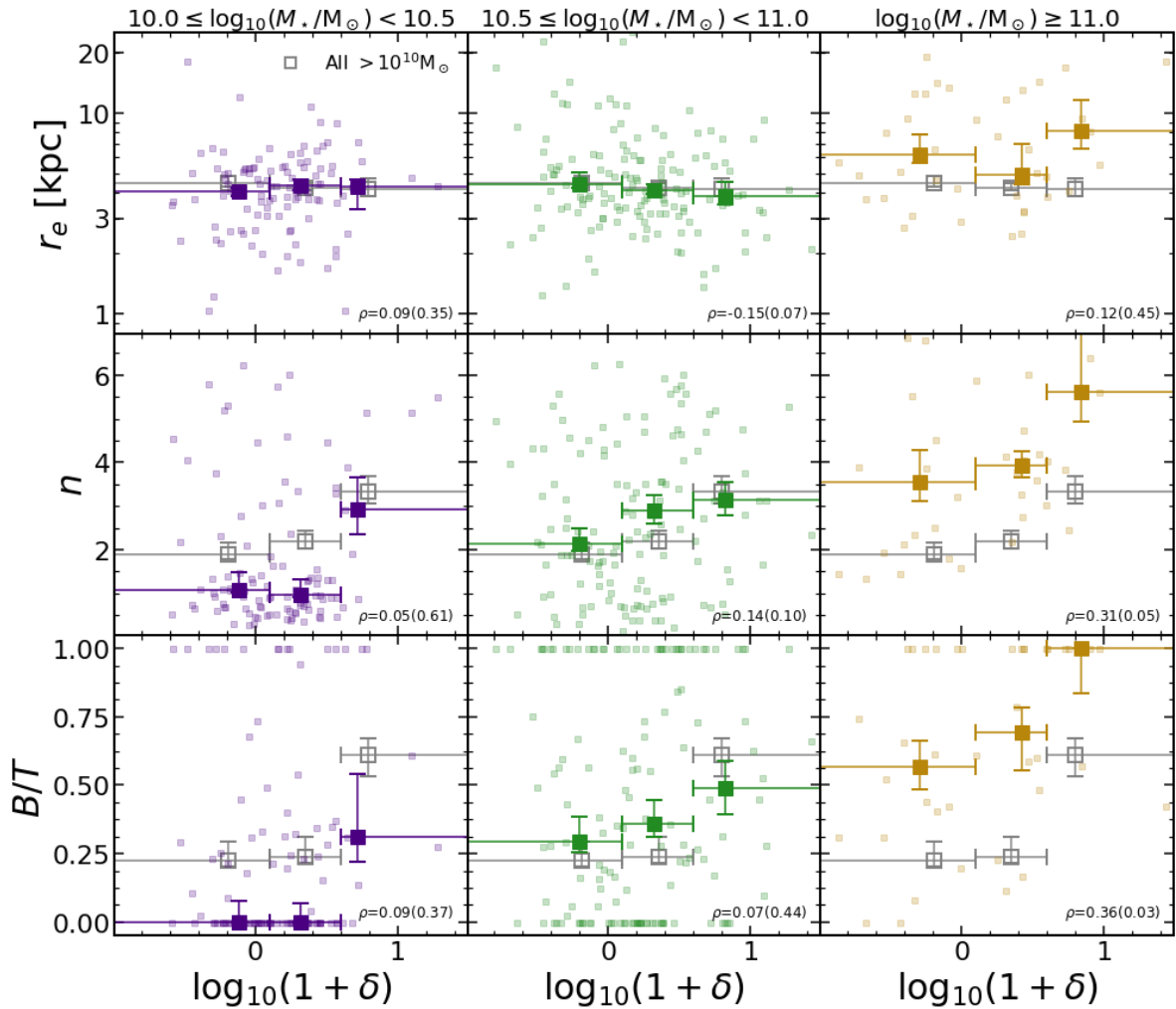


Fig. 2. The dependence of $z \sim 0.84$ galaxy sizes (top), Sérsic indices (middle), and the bulge-to-total ratio (bottom) on the environment for three different stellar mass bins (from left to right). We add to all panels the relation for the global sample at $M_{\star} > 10^{10} M_{\odot}$ as empty grey squares. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis. We find sizes are roughly constant across different environments but increase with stellar mass. In terms of their light profiles, we see a trend where both stellar mass and environment have an impact with more massive galaxies and denser environments showing larger values for n and B/T .

ronments having higher B/T values for fixed stellar mass. A similar trend for B/T as for the Sérsic index is seen, which is expected since the presence of a more prominent bulge should also produce a steeper light profile in the galaxy centre. Despite the differences observed in the median values, we do find the correlations with local density to be weak for the low- and intermediate-stellar mass bins ($\rho < 0.1$). The stronger correlation is observed when considering higher stellar mass galaxies ($\rho = 0.36$).

Our results highlight that galaxy morphology changes with the environment (at fixed stellar mass) and changes with stellar mass (at a fixed environment) at $z \sim 0.84$. We compute the average gradient of the median value for stellar mass and local density. We find that a variation in stellar mass implies a stronger change on the median morphological parameter when compared to a variation in local overdensity. This can also be seen in Fig. B.1, where we find stronger correlations with stellar mass for all shown quantities.

4.2. Non-parametric quantities

We summarize the results on non-parametric morphological tracers as a function of stellar mass and environment in Fig. 3. We find a clear dependence of the median light concentration on stellar mass, with more massive galaxies being more concentrated. We also find a trend with the environment, in which galaxies in denser environments have higher values of C . The correlation of C with local density is the strongest for the higher stellar mass bin ($\rho = 0.35$), being close to non-existent in the lower stellar mass bin ($\rho = 0.06$).

When considering the asymmetry of light profiles (see second row, Fig. 3), we find little dependence of the median asymmetry on both stellar mass and environment. For low-to-intermediate-stellar mass bins the correlation is weak to non-existent ($\rho < 0.1$). For the higher stellar mass bin there is a slightly stronger correlation ($\rho = 0.28$) than at lower stellar masses with galaxies in high-density regions being less asymmetric than those in lower density environments.

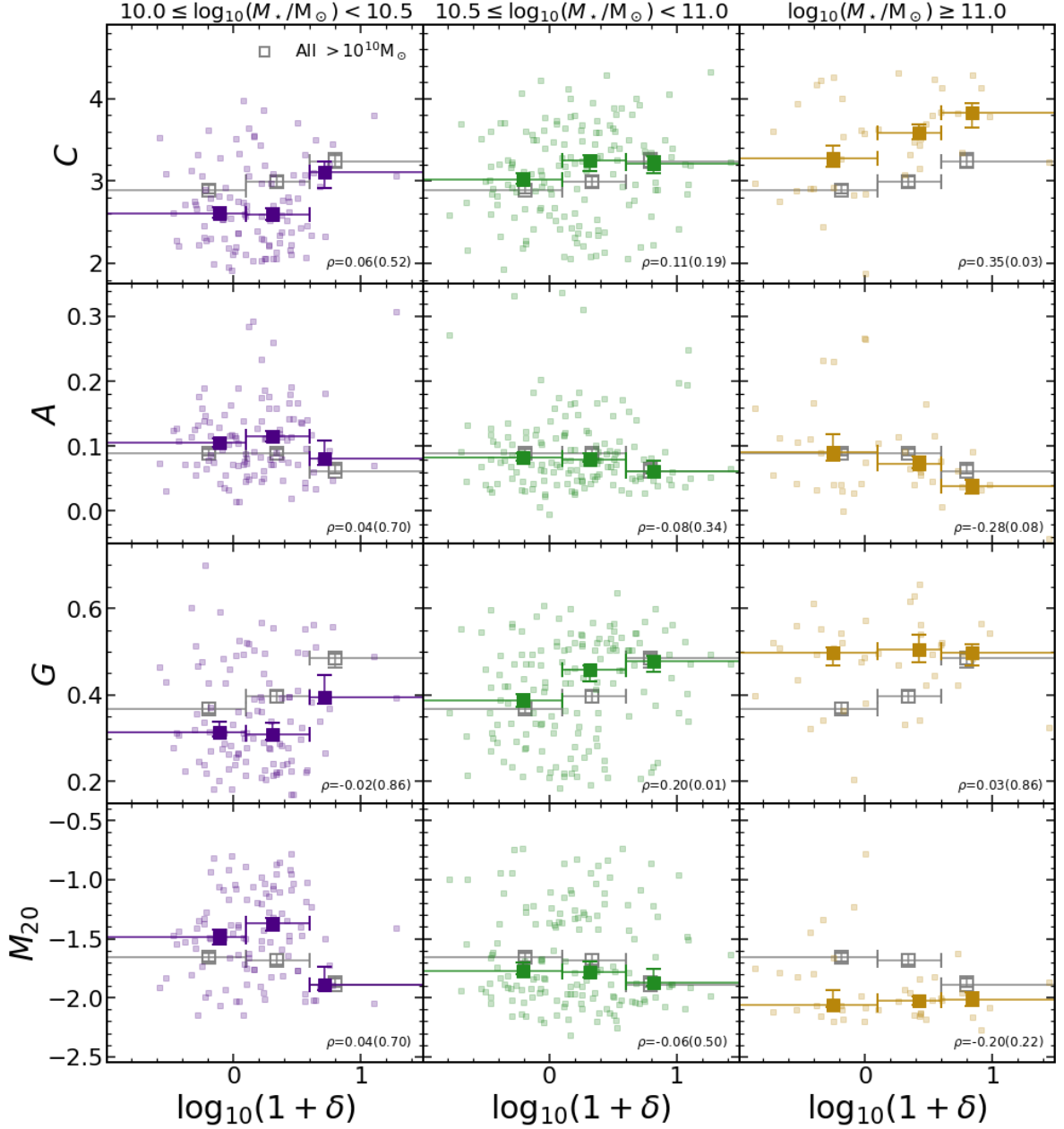


Fig. 3. The dependence of non-parametric tracers (from top to bottom: light concentration, asymmetry, Gini, and moment of light) on the environment for three different stellar mass bins (from left to right). We add to all panels the relation for the global sample at $M_\star > 10^{10} M_\odot$ as empty grey squares. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis. Overall we find that both stellar mass and environment have some impact on the non-parametric morphology, with stellar mass having the strongest impact on the median of the population (as measured by the average gradient)

The Gini coefficient displays a more interesting set of trends on the median of the population (see third row, Fig. 3). We find a clear trend with stellar mass, with more massive galaxies having higher Gini values (consistent with higher concentration). Concerning local density, we find that the trend depends on the stellar mass of the population. The lower stellar mass galaxies are similar in low- and intermediate-density environments, but then the Gini coefficient increases towards denser environments. For intermediate stellar mass galaxies, we find a slight trend of galaxies having larger Gini values from low- to high-density

environments. For the most massive galaxies in the sample, we find no environmental dependence. We note, however, that the correlation with local density is absent for the lower and higher stellar mass bins ($\rho < 0.05$), and only significant at intermediate stellar masses ($\rho = 0.2$ but only a $\sim 1\%$ probability of being an uncorrelated distribution).

In terms of the median moment of light, we find a clear trend with stellar mass, with higher stellar mass systems having lower values of M_{20} (less disturbed profiles, see fourth row in Fig. 3). In terms of environmental dependence, we find no significant dependence of the median for

the intermediate and high stellar mass bins. For the lower stellar mass galaxies, there is a drop in the value of M_{20} in the densest regions compared to a roughly constant value at lower densities. We note, however, that all of the correlations with local density are weak ($\rho = 0.2$ and $\sim 22\%$ probability of being an uncorrelated distribution at higher stellar masses) to non-existent ($\rho < 0.1$ at lower stellar masses).

5. Relation between galaxy structure/morphology and star formation

In this section, we explore the influence of star formation activity on galaxy structure and morphology by splitting our sample into star-forming and quiescent populations according to the NUV-r-J colour-colour diagram (e.g. Ilbert et al. 2013, see also Fig. 1). Since these two populations have been found to have different typical morphologies and structural parameters (see e.g. van der Wel 2008; van der Wel et al. 2014; Morishita et al. 2014), we want to quantify possible differences with stellar mass and environment produced by having different mixes of the star-forming and quiescent populations.

5.1. Galaxy sizes

We show in Fig. 4 (top panel) the relation between the median galaxy size (measured as the effective radius) as a function of stellar mass for quiescent and star-forming galaxies. We find a good agreement to a large sample at similar redshifts (van der Wel et al. 2014) as expected given that galaxies in VIS³COS are representative of the larger population at these redshifts. We note that for the quiescent sample van der Wel et al. (2014) only fits the stellar-mass-size relation using galaxies more massive than $10^{10.3}M_{\odot}$. They also apply a misclassification (possible confusion between star-forming and quiescent galaxies) correction that lowers the weight of large, quiescent galaxies and small star-forming galaxies in the joint fit of the stellar mass-size relations. This is likely the reason for the difference between our median value and their best fit relation at lower stellar masses. Regarding the correlation strength, we find a slightly stronger correlation for quiescent galaxies at $M_{\star} > 10^{10}M_{\odot}$ ($\rho = 0.47$ when compared to $\rho = 0.37$ for star-forming galaxies), but for both populations the correlations are significant, as already found by many studies (e.g. Franx et al. 2008; van der Wel et al. 2014; Morishita et al. 2014; Sweet et al. 2017; Mowla et al. 2019).

We split each population into three local density bins (see Figs. C.1 and C.2) to investigate the existence of any environmental dependence of galaxy sizes with environment at $z \sim 1$. For star-forming galaxies, we find no significant difference of the median values with local density as well as weak correlations for each stellar mass subsample. Our results are consistent with those reported by other studies (e.g. Lani et al. 2013; Kelkar et al. 2015; Tran et al. 2017). Though some studies find differences between field and cluster galaxies (e.g. Cebrián & Trujillo 2014; Allen et al. 2015, 2016, between 7% and 16% larger in cluster environments), these differences are smaller than our error bars and consistent with our results. Regarding the quiescent population we find no significant dependence with environment for galaxies with $10 < \log_{10}(M_{\star}/M_{\odot}) < 11$. This is also consistent with results from the literature tar-

geting similar stellar mass ranges (e.g. Huertas-Company et al. 2013b; Cebrián & Trujillo 2014; Newman et al. 2014; Allen et al. 2016; Saracco et al. 2017). For the most massive quiescent galaxies in our sample, we find larger sizes for galaxies in the highest local density bin when compared to the two lower density bins (see Fig. C.2). It is also the most massive galaxies which have the strongest correlation between size and local density ($\rho = 0.27$ and $\sim 17\%$ probability of being an uncorrelated distribution), despite not being as significant as that found for the stellar mass-size correlations. This is already hinted at in Fig. 2 and is found in other studies at these high stellar masses (see e.g. Papovich et al. 2012; Saracco et al. 2017; Yoon et al. 2017).

5.2. Prominence of galactic bulges

We explore the impact of stellar mass on the steepness of the light profiles in star-forming and quiescent galaxies. We show in Fig. 4 the median one-component Sérsic index for all galaxies. We find that quiescent galaxies have similar Sérsic indices, $n \sim 4$, at all stellar masses greater than $10^{10}M_{\odot}$, the typical value for classical ellipticals. For star-forming galaxies, we do find a rise of the median value of n with stellar mass, going from $n \sim 1$ at $10^{10.25}M_{\odot}$ to $n \sim 4$ at $>10^{11}M_{\odot}$. We note, however, that this rise in Sérsic index can be traced to a change in the structure of star-forming galaxies with stellar mass, from simple disks to disk+bulge systems. As we highlighted in Fig. 4, when considering only those galaxies for which the best fit is a single Sérsic (where the value of n is the better descriptor of the light profile shape) we find no trends with stellar mass, with the median value of n being the typical value for exponential disks $n \sim 1$. We attempt to split further our sample in overdensity bins to explore the impact of environment on galaxy structure and we find no little difference for samples in different environments (with the exception of a positive trend with environment - $\rho = 0.70$ - considering the 11 high stellar mass star-forming galaxies populating the two lower density bins, see Figs. C.1 and C.2).

We also show in Fig. 4 the median bulge-to-total light ratio (B/T) for quiescent and star-forming galaxies in different stellar mass bins. Overall we find quiescent galaxies to have higher values of B/T than star-forming galaxies at stellar masses greater than $10^{10}M_{\odot}$, which is expected given the more bulge-dominated nature of quiescent galaxies (e.g. Wuyts et al. 2011; Kim et al. 2018; Morselli et al. 2019). Regarding the trend with stellar mass, we find that both quiescent and star-forming systems show an increase of B/T with increasing stellar mass (weak, non-negligible correlation - $< 1\%$ - likely of being an uncorrelated distribution). In the quiescent population it rises from $B/T \sim 0.4$ to $B/T \sim 1$ (from $\sim 10^{10.25}M_{\odot}$ to $\sim 10^{11.25}M_{\odot}$) while for the star-forming population it rises from $B/T \sim 0$ to $B/T \sim 0.4$ in the same stellar mass interval. In Figs. C.1 and C.2 we show the dependence of B/T on environment for the shown stellar mass bins for both populations. In the case of star-forming galaxies, there is no significant trend with local density. For quiescent galaxies, we might see a hint of a trend when considering the median values for galaxies more massive than $10^{10.5}M_{\odot}$, but the correlations are very weak.

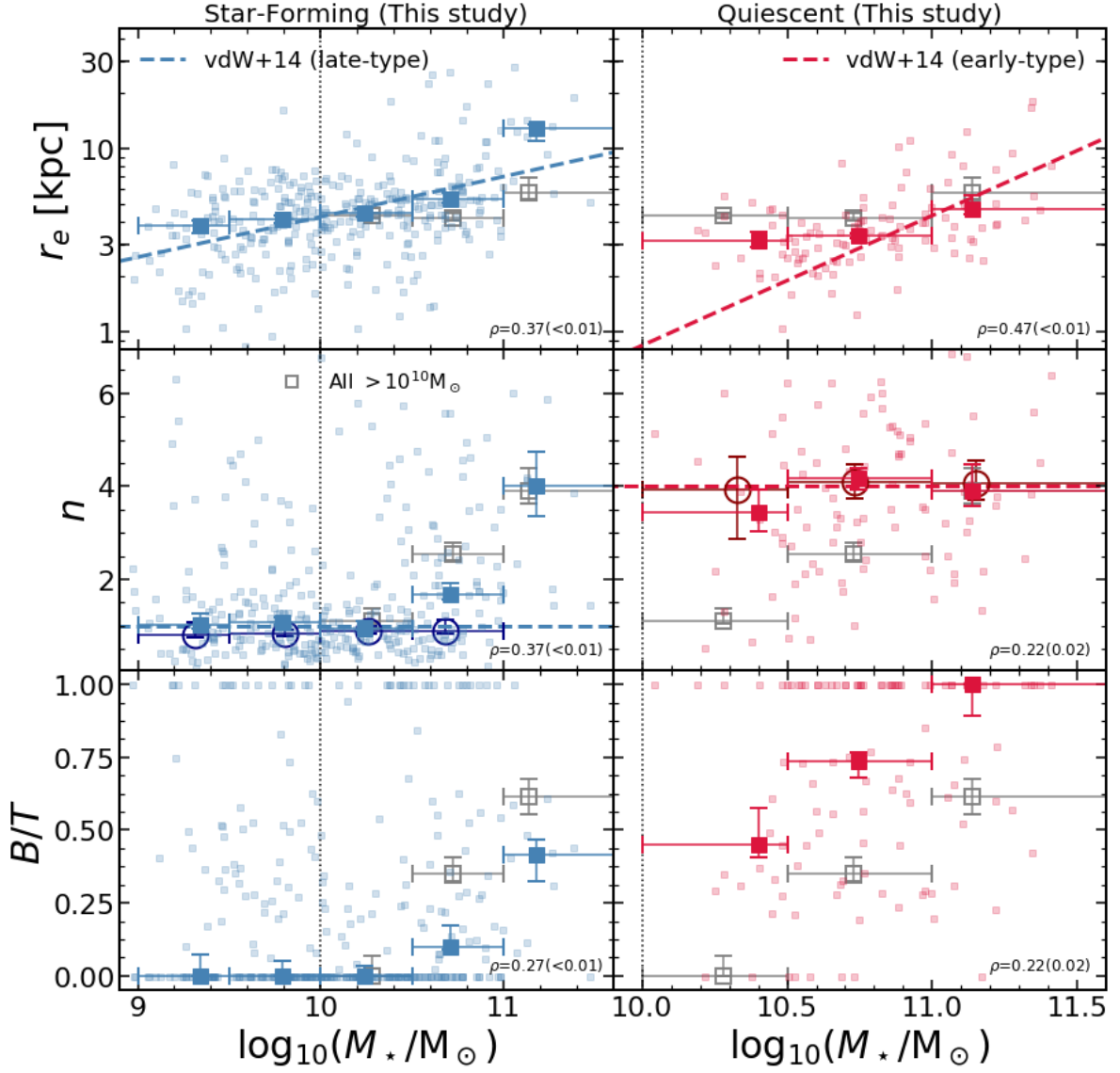


Fig. 4. Top: The stellar-mass size relation at $z \sim 0.84$ for all galaxies in our sample, divided in star-forming (left) and quiescent (right) subsamples. We also show the derived relation for a large sample at similar redshifts for star-forming (blue dashed line) and quiescent galaxies (red dotted line) derived by van der Wel et al. (2014). We find a good agreement between our sample and a magnitude-limited sample at these redshifts, indicating that our sample is representative of the larger population in terms of sizes and stellar masses. **Middle:** Sérsic index as a function of stellar mass for galaxies best fit by a single Sérsic profile. The median value for all galaxies shown with large squares, and for the subset of galaxies best fit with one component we show the median as large empty circles. We show as horizontal dashed lines the values for an exponential disk (blue, $n = 1$) and a classical elliptical (red, $n = 4$) profiles. The vertical dotted line highlights the stellar mass selection limit of our survey. We find star-forming and quiescent galaxies to align with the classical expectations at lower redshifts, with quiescent galaxies having profiles typical of ellipticals and star-forming galaxies those of typical disks. **Bottom:** Bulge-to-total light ratio as a function of stellar mass. The median is shown with large symbols. We find quiescent galaxies to have slightly more prominent bulges than star-forming galaxies at similar stellar masses. We add to all panels the relation for the global sample at $M_* > 10^{10} M_\odot$ as empty grey squares. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis (considering only $M_* > 10^{10} M_\odot$).

5.3. Morphology trends with a model-independent approach

As detailed in Section 3.2, there are a number of quantities that can describe the light profiles of galaxies without the assumption of a physical model. In Fig. 5, we present the properties of star-forming and quiescent galaxies as a function of stellar mass. We find that quiescent galaxies have higher concentration indices than star-forming galaxies at all stellar masses. We also find that higher stellar mass galaxies (from $\sim 10^{10.25} M_\odot$ to $\sim 10^{11.25} M_\odot$) have higher

concentration values in both populations (correlations with stellar mass are equally strong for both populations). In quiescent galaxies the median value of the light concentration (C) rises from 3.29 ± 0.05 up to 3.64 ± 0.09 and in star-forming galaxies it rises from 2.54 ± 0.05 to 3.0 ± 0.1 . The fact that quiescent galaxies have higher concentration values than their star-forming counterparts is consistent with them having elliptical or bulge-dominated morphologies.

We also show in Fig. 5 the median asymmetry of galaxy light profiles. We find that neither star-forming nor quiescent galaxies' asymmetry is correlated with their stellar mass (low correlation coefficient, no significant change in the median values). Considering galaxies above our stellar mass selection limit ($10^{10}M_{\odot}$), we find quiescent galaxies to have lower asymmetry ($A \sim 0.05 - 0.06$) than star-forming galaxies ($A \sim 0.10 - 0.12$) at all stellar masses. This difference in asymmetry indicates that quiescent galaxies have smoother light profiles when compared to star-forming galaxies, which have a clumpier light profile due to blue star-forming clumps.

In Fig. 5 we show the results of a different set of morphology diagnostics. We find that quiescent galaxies have a higher percentage of their light concentrated on a smaller area (higher Gini coefficient - G) when compared to star-forming galaxies at similar stellar masses. Considering galaxies with stellar masses above $10^{10}M_{\odot}$, we find a negligible increase in the median value of G for quiescent galaxies (from 0.49 ± 0.02 to 0.52 ± 0.01) and a steeper increase for star-forming galaxies (from 0.30 ± 0.01 to 0.37 ± 0.02). The correlation coefficient also points to a stronger trend for star-forming galaxies, despite the large scatter. When considering the value of the moment of light (M_{20}), which measures the concentration of the brightest regions and is sensitive to the existence of multiple clumps, we find a global trend for galaxies with high stellar mass to have lower values of M_{20} (higher concentration of the brightest regions, irrespective of clumpy sub-structures). We find non-negligible, but weak, correlations with stellar mass for both populations. We also find quiescent galaxies to have higher flux concentration when compared to star-forming galaxies of similar stellar masses. The combination of these two quantities highlights the difference between quiescent galaxies having a higher concentration of their flux and less likely to have clumpy substructures when contrasted to their star-forming counterparts.

We split both populations in different bins of local density and find no statistically significant differences among different environments at fixed stellar mass bins for each population in all the presented tracers (see Figs. C.3 and C.4). The trends reported in this section all hint at quiescent galaxies having morphologies characteristic of elliptical (or bulge-dominated) light profiles whereas star-forming galaxies resemble more exponential disks with a larger degree of clumpiness/asymmetry in their light profiles.

5.4. Local density impact on visual morphology

We have defined in Section 3.3 three different morphological classes based on Galaxy Zoo classifications of HST data. In this section, we explore the impact of local density on the fraction of galaxies for each of the defined classes: ellipticals, disks, and irregulars. We restrict our analysis to galaxies more massive than $10^{10}M_{\odot}$ (our selection limit).

Fig. 6 reveals the differences in the fraction of observed morphologies for all massive galaxies in our sample. At lower densities (field- and filament-like regions) we find fractions of disk galaxies to be similar ($48 \pm 6\%$ and $51 \pm 8\%$, respectively). The same scenario applies to elliptical galaxies ($34 \pm 6\%$ and $28 \pm 6\%$, respectively) and irregular galaxies ($17 \pm 4\%$ in both local density bins). As we move towards higher density regions, we find an increase in the fraction

of elliptical galaxies (up to $69 \pm 23\%$) and a strong decline in the fraction of disk galaxies (down to $13 \pm 7\%$). For irregular galaxies, there is a small drop to $9 \pm 4\%$ and then rise to $19 \pm 9\%$ towards the highest densities, but our values are consistent with a constant fraction at all local densities. This result hints at an established morphology-density relation at $z \sim 0.84$.

We note, however, that we discussed in the Sections. 5.1-5.3 that if we split our sample into star-forming and quiescent populations, we find little effect of local environment on quantitative morphology within each population. We also explore here the fraction of each class for these two populations in Fig. 7. For quiescent galaxies, we find that the fraction of ellipticals dominates at all environments, and we observe no change with local density (nearly constant fraction at $\sim 60\%$). For quiescent galaxies with disk morphology, we find a constant fraction in the field- and filament-like densities ($\sim 35\%$) and then a drop towards higher densities (down to $7 \pm 5\%$). We find that quiescent galaxies with irregular morphologies are $\sim 7\%$ at lower density regions and then rise to $21 \pm 10\%$ in the highest density bin, surpassing the fraction of disks at these densities, indicating an increase in galaxy interactions at the higher densities.

For star-forming galaxies, we find disk morphologies to be the most common class at all densities ($\sim 57\%$) with little change across different densities. For star-forming ellipticals, we find a nearly constant fraction for the three lower density bins (at $\sim 30\%$) and then rise to $50 \pm 15\%$ at the highest density bin. We also find a decrease in the fraction of irregular star-forming galaxies from the field- and filament-like regions ($\sim 20\%$) down to 0% at the highest density bin in the sample.

Our results hint at an effect of local density on galaxy morphology. On the quiescent population, we see a trend of change from red disk galaxies to irregular galaxies, likely related to the tidal disruption of galactic disks by interactions with other cluster members. On the star-forming population, we see a change of disk and irregular galaxies into elliptical galaxies, likely through mergers (e.g. Bournaud et al. 2007; Kormendy et al. 2009; Taranu et al. 2013; Martin et al. 2018).

6. Discussion

We study galaxy morphology on a sample of ~ 500 spectroscopically confirmed galaxies in and around a superstructure in COSMOS at $z \sim 0.84$. Although we find that galaxies' morphological measurements depend on both environment and stellar mass, when we split the sample into star-forming and quiescent systems, such morphological trends weaken significantly or vanish completely. In the following, we try to explain this with a simple model.

6.1. Structural dependence predicted from the quiescent fraction

In Section 5 we find that there is a small dependence of structural measurements on stellar mass for galaxies split into star-forming and quiescent (see e.g. Sérsic index in Fig. 4). We also find little or no dependence of morphological indicators (both quantitative and qualitative) on local density when we split the sample into star-forming and quiescent systems (see Figs. C.1 through C.4). We also show (see e.g.

Figs. 2, 3, and 6) that we find structural and morphological dependence on stellar mass and environment when considering the global sample at stellar masses $>10^{10}M_{\odot}$. We attempt here to explain the observed changes with density as a consequence of the change in the fraction of each population (star-forming or quiescent) that is present at each environment and stellar mass bin.

Paulino-Afonso et al. (2018b) show the dependence of the quiescent fraction on stellar mass and environment for galaxies more massive than $10^{10}M_{\odot}$, where they find that it strongly increases with stellar mass and also from intermediate to high-density regions (see also e.g. Peng et al. 2010b; Cucciati et al. 2010; Muzzin et al. 2012; Darvish et al. 2014, 2016, 2018; Hahn et al. 2015). To test our assumption we assume that the average property x in a given stellar mass or environment bin is a combination of the individual properties of each population weighed by its fraction in that bin. We can then parametrize the dependence of x on stellar mass or environment as a function of the fraction of quiescent galaxies f_Q on the binned quantity:

$$x = \frac{x_{\text{SF}}N_{\text{SF}} + x_QN_Q}{N_T} = x_{\text{SF}}(1 - f_Q) + x_Qf_Q. \quad (1)$$

We can then use this to predict the expected values of any property if the fraction of quiescent objects is the driving influence of the observed dependencies. For example, we can derive the median B/T as a function of stellar mass or environment, assuming that all star-forming galaxies have $B/T = 0$ (exponential disks) and all quiescent galaxies have $B/T = 1$ (classical ellipticals). To compute the median properties from our observations, we also assign a value of B/T for galaxies best fit with a single Sérsic profile ($B/T = 0$ if $n < 2.5$ and $B/T = 1$ if $n > 2.5$, see Section 4.1). We show in the bottom panel of Fig. 8 the resulting prediction compared to the median observed values of B/T . We can apply this method to other quantities, and we highlight the light profile shape traced by parametric (Sérsic index n) and non-parametric (light concentration C) quantifications of galaxy structure in Fig. 8. For the case of n we use a constant value of $n_{\text{SF}} = 1$ and $n_Q = 4$ (based on single Sérsic best fit relations illustrated on Fig. 4). Considering the median observed value of n per bin of stellar mass, we can broadly reproduce the trend, albeit the trend with stellar mass is steeper (stronger variation, meaning a stronger underlying correlation with stellar mass for the sub-populations) than what is predicted from the quiescent fraction. In terms of the dependence with the environment, we find a remarkably good agreement between the two independent quantities (median n and f_Q). We find a similar result when considering the model independent light concentration C as the morphology tracer (using a simple constant value of $C_{\text{SF}} = 2.5$ and $C_Q = 3.5$ in equation 1).

Since we assume the most straightforward dependence of structural parameters with stellar mass and environment for each population, a constant value, it is natural that the discrepancy between the predicted and observed values is larger when our assumption of constancy is farther from the truth. Moreover, since the correlations of the studied parameters with local density are the weakest of the two, we find that our predictions match better with the observed median values in this case. The good agreement between the observed and the predicted value from our straightforward model is a strong argument in favour

of the morphology-density relation being tightly correlated with the fraction of quiescent/star-forming galaxies in different environments (e.g. Calvi et al. 2018). It is also consistent with the strongest impact of environment seeming to be to set the quiescent fraction (e.g. Darvish et al. 2014, 2016, 2018). It also means that processes that affect galaxy morphology, either in the formation of galaxies or posterior interactions, also impact star formation (e.g. Martig et al. 2009; Wuyts et al. 2011), although they might happen at different stages in their evolution (e.g. Bundy et al. 2010).

It is possible that the growth of a bulge is induced by a higher rate of interactions in higher density environments since several studies point to major and minor mergers as mechanisms for bulge growth (e.g. Eliche-Moral et al. 2006; Hopkins et al. 2010; Querejeta et al. 2015; Brooks & Christensen 2016). In the local Universe, merger-induced star formation is important (e.g. Lambas et al. 2012; Ellison et al. 2013; Scudder et al. 2015) and can play a role in the change of not only galaxy colour (see also e.g. Ellison et al. 2018), but also structure required to explain the observations in our study. In this scenario, the bulge prominence is correlated with the probability of the galaxy being quenched, with the quenched fraction being higher for high B/T systems (see e.g. Lang et al. 2014). A natural consequence of this is that B/T (and also more generally the Sérsic index and light concentration which measures similar properties) ratio of galaxies is correlated with f_Q , as we show in Fig. 8 (see also Kim et al. 2018).

6.2. Morphology-density relation at $z \sim 0.84$

Some studies show evidence for a correlation between morphology and environment up to $z \sim 1$ (e.g. Tasca et al. 2009). We find that such a relation is also present in our sample (see Fig. 6). However, we also show that the impact of local density on the galaxy structure among blue star-forming and red quiescent galaxies is negligible. What we find is consistent with the fraction of red/blue galaxies changing with environment and morphology tracing that change as well (see Fig. 8). This again hints that, as discussed before, the environment is mostly correlated with the quenched fraction, and does not affect the morphology of star-forming or quiescent galaxies at $z \sim 1$.

The differences in galaxy morphology for quiescent and star-forming galaxies have long been studied and established up to $z \sim 1$ (e.g. Strateva et al. 2001; Bamford et al. 2009; Mignoli et al. 2009; Wuyts et al. 2011; Whitaker et al. 2015; Krywult et al. 2017). Other studies show that the environmental dependence of galaxy morphology is tightly correlated with colour (Poggianti et al. 2008; Skibba et al. 2009; Bait et al. 2017). This is in agreement with our findings that when splitting our sample for star formation activity, the dependence with the environment is small (see also e.g. Papovich et al. 2012; Huertas-Company et al. 2013a,b; Lani et al. 2013; Cebrián & Trujillo 2014; Newman et al. 2014; Kelkar et al. 2015; Allen et al. 2015, 2016; Saracco et al. 2017). The existence of such correlation hints at a coherent transformation both in star formation and morphology for galaxies in different environments. This has already been seen in some studies targeting green valley galaxies (with colours in-between the red sequence and the blue cloud) where morphologies in-between exponential disks and classical ellipticals are found (e.g. Mendez et al. 2011; Coenda et al. 2018; Gu et al. 2018). However, a difference in

colour does not always translate to a difference in morphology for these sources (e.g. Schawinski et al. 2014; Vulcani et al. 2015) and both internal and external processes are required to explain such evolution across the green valley (e.g. Mahoro et al. 2017; Kelvin et al. 2018; Nogueira-Cavalcante et al. 2018).

The local morphology-density relation has a category of galaxies that plays a pivotal role in the observed trends that is not included in our analysis of visual morphology (S0 galaxies, e.g. Dressler 1980, 1984). However, they are less common at higher redshifts ($z \sim 0.5 - 0.8$ e.g. Dressler et al. 1997; Desai et al. 2007; Poggianti et al. 2009; Just et al. 2010). Given the existing classifications, S0 galaxies can fall into either the disk or elliptical categories, depending on the inclination with respect to the line-of-sight. Edge-on S0s are more likely to be classified as disks, while face-on S0s can be mistaken by ellipticals using our scheme. This means that we are not exploring the full scenario of morphological transformation in dense environments, but rather a simplified version of this correlation, considering only the two major classes of the original Hubble (1926) classification scheme (spiral disks and ellipticals). A more refined classification scheme would require a specific classification scheme with an identifiable option for S0 galaxies and a larger sample to be able to statistically disentangle the larger number of classes we would have to deal with, but this is out of the scope of this manuscript.

7. Conclusions

We study the influence of stellar mass and environment on galaxy morphology with the VIS³COS survey in and around a superstructure at $z \sim 0.84$ in the COSMOS field. We present our results on the bulge-to-disk decomposition of light profiles, non-parametric morphology, and visual classification. We also study separately star-forming and quiescent galaxies selected in the NUV-r-J colour space. A summary of our results is presented below:

- There is an environmental dependence of Sérsic indices and B/T in different stellar mass bins when considering the entire sample, with denser environments having galaxies with higher Sérsic indices and B/T for fixed stellar mass.
- We find that stellar mass is a stronger predictor of galaxy structure and morphology (stronger correlations) than local density for all quantities studied here.
- We find that for galaxies more massive than $10^{11}M_{\odot}$ there is an increase in size ($\sim 40\%$) from low- and intermediate-density regions to high-density regions. Less massive (between $10^{10}M_{\odot}$ and $10^{11}M_{\odot}$) galaxies show no dependence on local density.
- Quiescent galaxies are smaller than their star-forming counterparts at similar stellar masses. We find no difference between different environments for star-forming galaxies. For quiescent galaxies, we see a change in galaxy sizes from low- and intermediate- to high-density regions in the most massive bin ($>10^{11}M_{\odot}$), which drives the differences found when looking at the full sample.
- Galaxies best fit with a single profile show a clear morphology-colour dichotomy. Quiescent galaxies have median Sérsic indices comparable to classical ellipticals

($n \sim 4$), and star-forming galaxies show profiles close to exponential disks ($n \sim 1$).

- We also find differences in light profiles with non-parametric morphology. Quiescent galaxies have smoother profiles (lower asymmetry and M_{20}) and have more concentrated light profiles (higher concentration and Gini coefficient) than star-forming galaxies.
- We find evidence for the existence of a morphology-density relation at $z \sim 0.84$ when looking at the sample as a whole, but less pronounced when splitting into star-forming and quiescent sub-samples.
- When combined, our results point to a tight correlation between morphology and colour, with quiescent and star-forming galaxies showing little dependence on the environment. We can reproduce the observed trends of structure and morphology (traced by B/T , n , and C) with a local density as a natural consequence of the change in the quenched fraction for different environments.

We thus find that environmental dependencies of galaxy structure and morphology exist when considering the entire sample. However, those dependencies are much less pronounced when considering only the star-forming or the quiescent subsamples. Based on our results, we argue that both colour and structure/morphology are affected by environment, and this is manifested through a varying fraction of blue disks to red ellipticals from low- to high-density regions. Such a tight correlation between star formation and morphology implies that physical mechanisms responsible for regulating star formation must also act in changing the structure and morphology of galaxies, such as galaxy mergers or strong feedback events. The subtle effects of both the stellar mass and environment allow for better constraints on the possible scenarios for galaxy evolution across different environments. A better sampling of galaxies in the transition phase (in filaments and/or in the green valley) is necessary to better pinpoint the mechanisms responsible for the observed changes with stellar mass and environment.

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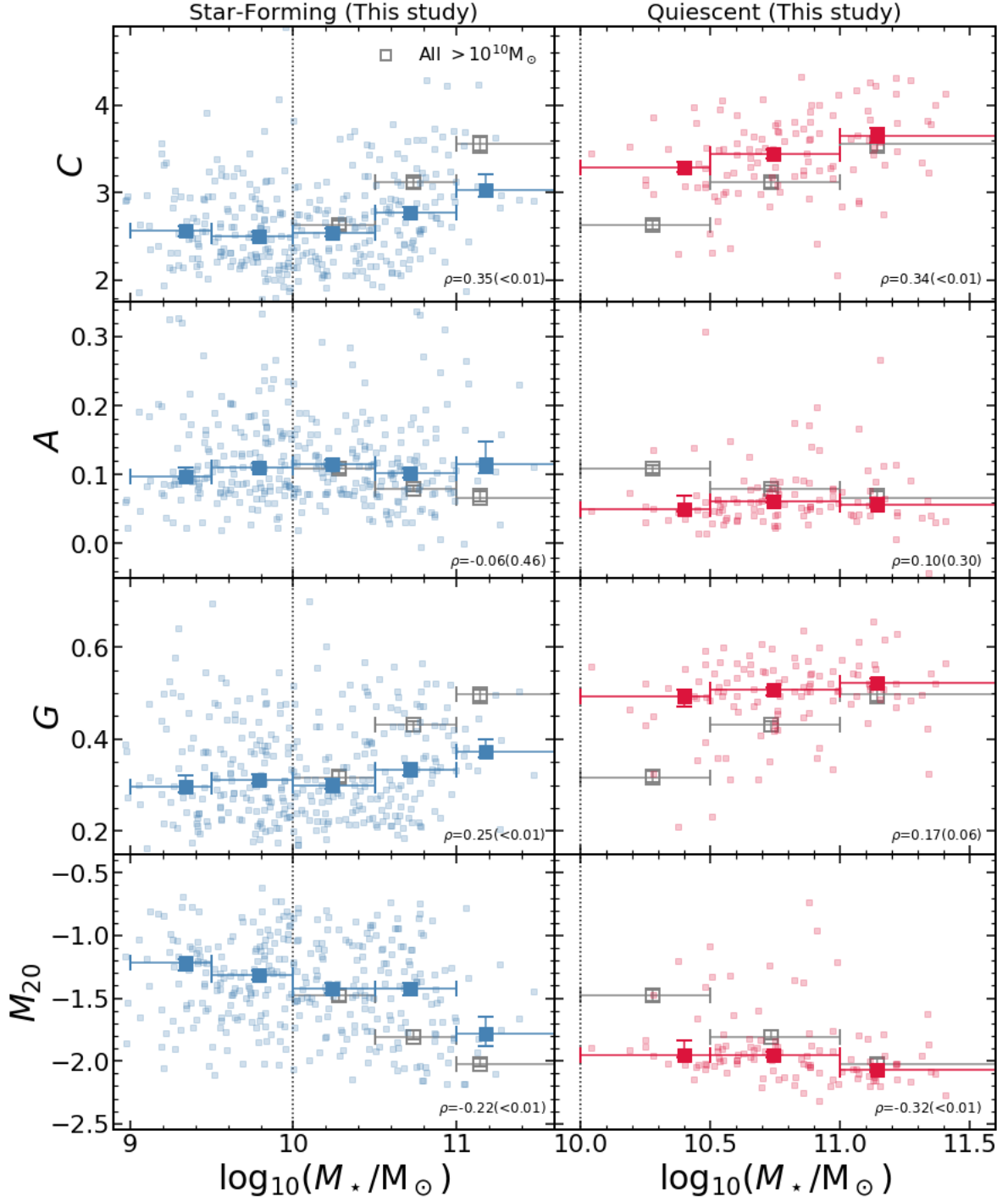


Fig. 5. Light concentration (top), image asymmetry (middle top), Gini coefficient (middle bottom) and moment of light (bottom) as a function of stellar mass. We add to all panels the relation for the global sample at $M_{\star} > 10^{10} M_{\odot}$ as empty grey squares. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis (considering only $M_{\star} > 10^{10} M_{\odot}$). We find quiescent galaxies to have a higher concentration of light than star-forming galaxies at similar stellar masses. We also find quiescent galaxies to have less disturbed profiles at stellar masses greater than $10^{10} M_{\odot}$. This is likely a reflection of the lack of star-formation that is clumpier in nature (Conselice 2003). We also find quiescent galaxies to have their light concentrated on a smaller area (higher value of G) than star-forming galaxies at similar stellar masses. Finally, quiescent galaxies are smoother (lower values of M_{20}) at all stellar masses, as also seen in the asymmetry parameter.

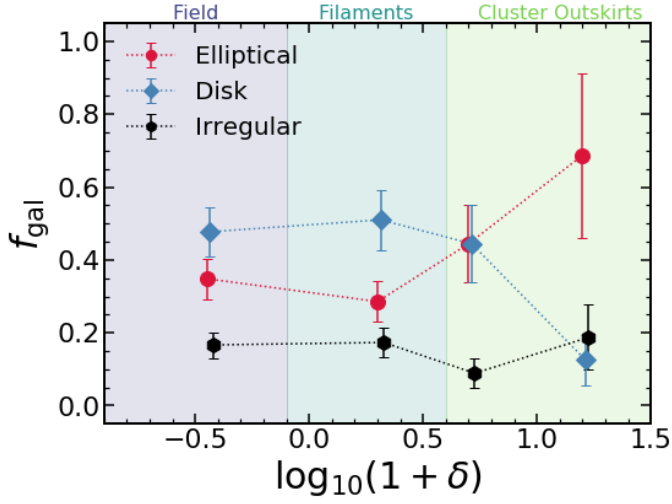


Fig. 6. The fraction of galaxies more massive than $10^{10}M_{\odot}$ of a given galaxy morphology (see Section 3.3) as a function of local density. Errors on the fractions are computed from Poisson statistics. We show as coloured vertical regions the likely association between local density and density regions. We note that we find no significant differences between field-like and filament-like densities. We do find a rise in the fraction of ellipticals and a decline of disk-like morphologies towards the densest regions probed here.

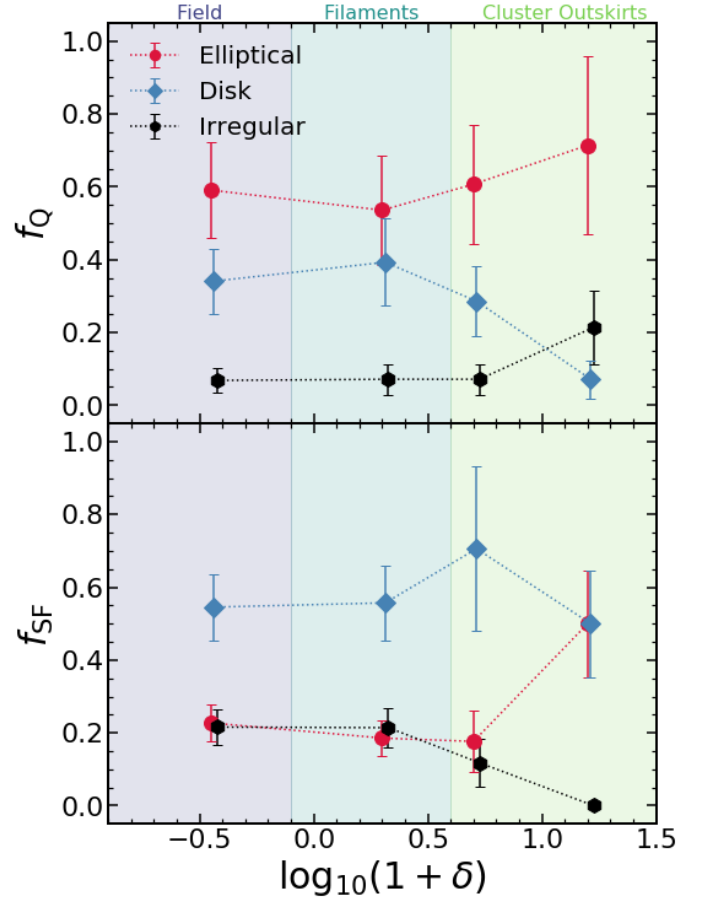


Fig. 7. The fraction of galaxies more massive than $10^{10}M_{\odot}$ of a given galaxy morphology (see Section 3.3) as a function of local density for quiescent (top) and star-forming (bottom) galaxies. Errors on the fractions are computed from Poisson statistics. We show as coloured vertical regions the likely association between local density and density regions. For quiescent galaxies, we see a nearly constant fraction of elliptical galaxies with density and an increase in irregular morphologies at the expense of disk galaxies in the densest regions. For star-forming galaxies, we might find a small trend in the densest bin with an increase in ellipticals and a decline in irregular galaxies (and also potentially disks, though the disk fraction is compatible with no environmental influence).

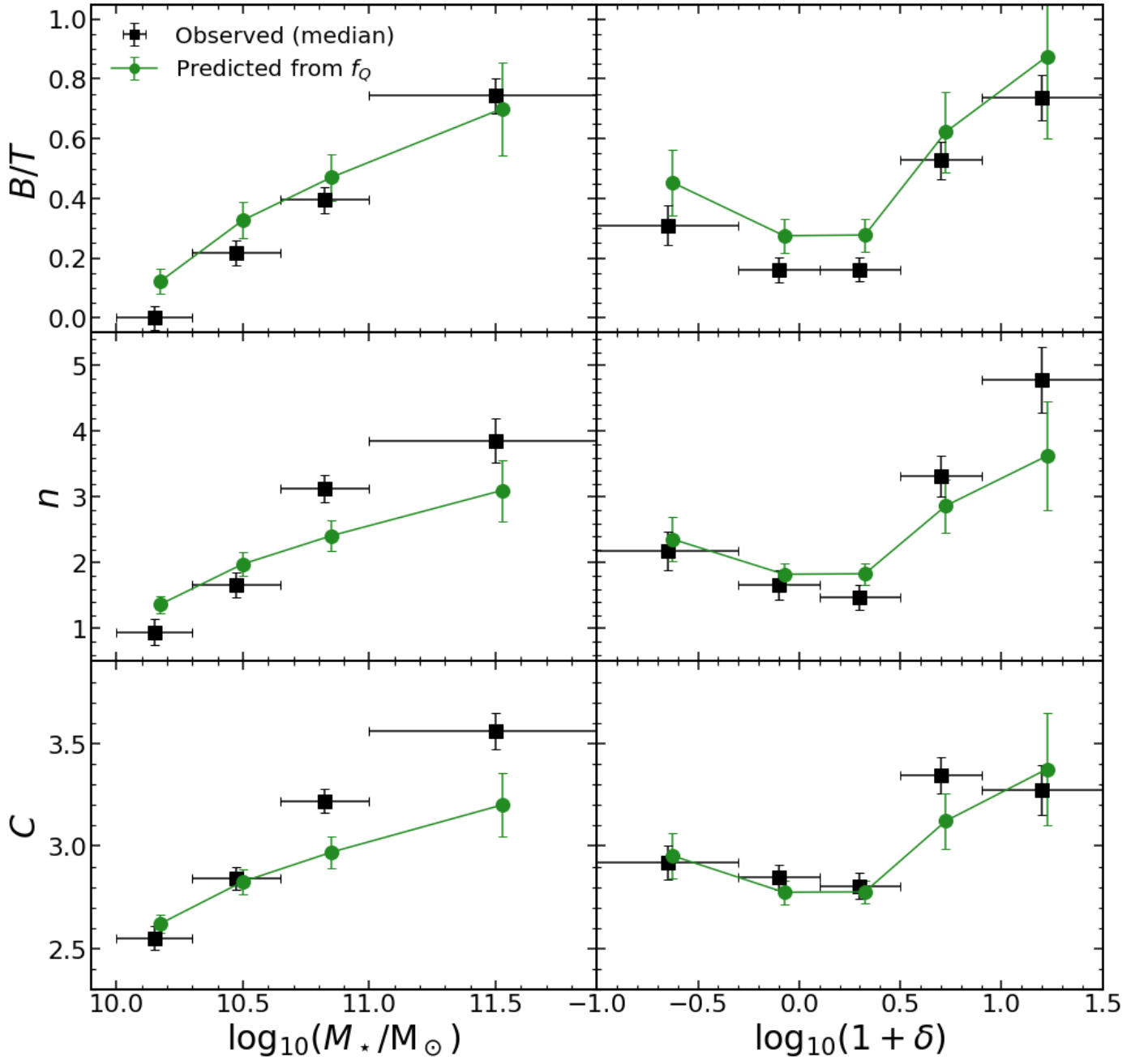


Fig. 8. The predicted (green circles) and observed median (black squares) values of the bulge-to-total light ratio (top), Sérsic index (middle) and light concentration (bottom) for galaxies more massive than $10^{10}M_\odot$. The predicted values are based on a simple model (see Section 6.1) that predicts stellar mass or environmental dependence of any property based on the fraction of quiescent/star-forming galaxies at different stellar masses and in different environments. We find a good agreement between predicted and observed values, indicating that the perceived effects of galaxy structure/morphology on stellar mass and environment are tightly correlated with the fraction of star-forming and quiescent populations in each bin.

Appendix A: Technical details on morphological parameters

Appendix A.1: Statistical choice on best fit parametric model

One is free to choose a model with as many components as one wants to fit every galaxy. However, to get physically meaningful results from fitting galaxy images, one should take caution with over fitting the data by choosing models that are too complex when compared to what is needed to fit the actual data. There have been some statistical criteria to decide whether or not a complex model should be used (e.g. Simard et al. 2011; Kelvin 2012; Meert et al. 2013; Bruce et al. 2014b; Margalef-Bentabol et al. 2016). The Bayesian Information criterion, e.g. used by Kelvin (2012) and Bruce et al. (2014b), is a measure of how good a model fits the data one wants to describe. In the case of nested models, it penalizes those with a higher number of free parameters. It is described by

$$BIC = \chi^2 + k \ln(N), \quad (A.1)$$

where χ^2 is the measure of the global goodness of the fit given by GALFIT, k is the number of the free parameters of the model we are considering and N is the number of contributing data points to the analysis of the model that is taken to be the area, in pixels, of the object we are considering. Given two models we can compute the difference in this estimator with

$$\Delta BIC = BIC_c - BIC_s = (\chi_c^2 - \chi_s^2) + (k_c - k_s) \ln(N), \quad (A.2)$$

where s and c denote the simple (one profile) and complex (bulge+disk) models, respectively. The preferred model is the one with the lower BIC value. In a strict sense, if $\Delta BIC < 0$ then the complex model is to be chosen over the simplest one. However, to be sure that the complex model is more than just simply marginally better than a single profile, we apply a stricter rule for which $\Delta BIC < -10$ (e.g. Kelvin 2012).

Appendix A.2: Non-parametric computation

Appendix A.2.1: Light concentration

The concentration index C is defined as the ratio of the 80% to the 20% curve of growth radii within 1.5 times the Petrosian (1976, r_p) radius for a parameter $\eta = F(r)/\int_0^r F(r) = 0.2$ (see e.g. Bershadsky et al. 2000). With that radius we compute the flux using elliptical apertures centred on the light-weighted centre of the galaxy up to which 20% and 80% of the light is contained. Then, we compute C via

$$C = 5 \log \left(\frac{r_{80}}{r_{20}} \right). \quad (A.3)$$

This parameter allows separating between concentrated objects such as ellipticals from more extended sources such as spirals or irregulars. Using this definition the values of C range from about 2 to 5, where $C > 4$ usually indicates spheroidal like systems, $3 < C < 4$ disk galaxies and the lower values of C are from low surface brightness objects or sometimes from multi-component systems (see e.g. Conselice 2003).

Appendix A.2.2: Asymmetry

The asymmetry index A measures the strength of non-axis-symmetric features of an image I by comparing it to a 180 degrees rotated version of itself, I^{180} . Since we expect asymmetric features on irregular galaxies usually associated with galaxy-galaxy interactions, this index is very useful to identify on-going galaxy mergers. It also correlates with on-going star formation as individual star-forming regions in a larger galaxy can also produce asymmetric flux distributions (Bershadsky et al. 2000; Conselice et al. 2000; Conselice 2003). We compute the index A as

$$A = \frac{\sum_{i,j} |I_{i,j} - I_{i,j}^{180}|}{\sum_{i,j} I_{i,j}} - B_{180}, \quad (A.4)$$

where $I_{i,j}$ is the intensity at the pixel (i,j) and B_{180} is the intensity of the background asymmetries. The centre around which the image is rotated is an important parameter, and there are difficulties in having a well-defined galaxy centre. We follow the method of Conselice et al. (2000) and iterate the centre position following a gradient-step approach starting from the light-weighted centre to find the local minimum of A within the segmentation map. To compute B_{180} , we use the median of 100 different sky patches of the same size of the image on which we compute A and extract from regions around the object of interest.

Appendix A.2.3: Gini coefficient

The Gini coefficient, G , measures the concentration of light within the pixels belonging to the galaxy's segmentation map. There is some correlation between G and C simply because more concentrated galaxies tend to have their light distributed over a small number of pixels, therefore, leading to high values of G and C . Reversely, low and shallow surface brightness profiles tend to have their light more equally distributed, leading to lower values of G and C . However, the Gini coefficient will differ from the Concentration parameter in those cases where there is a concentration of high flux pixels away from the projected centre of the galaxy (e.g. multi-clump galaxy). This index is derived from the Lorenz curve that is a rank-ordered cumulative distribution function of a galaxy's pixel values:

$$L(p) = \frac{1}{\bar{X}} \int_0^p F^{-1}(u) du, \quad (A.5)$$

where $F(u)$ is the cumulative distribution function, p is the percentage of the fainter pixels normalized, and \bar{X} is the mean pixel flux. The Gini coefficient is then defined as the ratio of the curve $L(p)$ and the equality curve $L(p) = p$. In a discrete population, it can be computed as

$$G = \frac{1}{2\bar{X}n(n-1)} \sum_{i,j}^n |X_i - X_j|, \quad (A.6)$$

where n is the number of pixels of the galaxy. $G = 0$ if all the pixels have the same nonzero flux and $G = 1$ if all the flux is contained in one pixel. An efficient way to compute this coefficient is to first sort the pixels of the galaxy in increasing order of flux and then compute simply

$$G = \frac{1}{\bar{X}n(n-1)} \sum_i^n (2i - n - 1) X_i. \quad (A.7)$$

Since this coefficient takes into account all pixels of the object, it is very sensitive to the segmentation map associated with the galaxy (see Lotz et al. 2004). The inclusion of background flux will increase the value of G while not taking into account low surface brightness pixels will decrease its value. We note that direct comparison to other results in the literature needs to be done with caution as different definitions of the segmentation map can yield different Gini values for the same galaxies. While this affects the absolute value of G , any relative comparison within our sample is valid since it is all computed using the same definition for the segmentation map.

Appendix A.2.4: Moment of light

The index M_{20} is also a measure of light concentration. However, being independent of a specific definition of centre or on having elliptical/circular apertures is less sensitive to asymmetries in the light profile. It is thus a more robust measure for galaxies with multiple bright clumps within a single segmentation map. The total second order moment M_{tot} is computed by summing the flux in each pixel I_i multiplied by the squared distance to the centre of the galaxy. In this case, the centre of the galaxy is that which minimizes M_{tot} :

$$M_{tot} = \sum_i^n I_i [(x_i - x_c)^2 + (y_i - y_c)^2]. \quad (\text{A.8})$$

The index M_{20} is then the normalized sum of the brightest 20% pixels values taken from a list of intensity sorted values in a descending order

$$M_{20} = \log_{10} \left(\frac{\sum_i^N I_i [(x_i - x_c)^2 + (y_i - y_c)^2]}{M_{tot}} \right) \quad (\text{A.9})$$

with the sum considering the pixels that obey $\sum I_i < 0.2I_{tot}$ where I_{tot} is the total flux of the galaxy inside the segmentation map region. We normalize by M_{tot} so that this parameter is independent of either total flux or galaxy size.

Appendix A.3: Visual classification selection

To create subsets of different morphological types (elliptical, disk, or irregular, see e.g. Paulino-Afonso et al. 2018a) we use mainly the results from the first and second tiers (Willett et al. 2017, Figure 4). In a brief explanation, the user is presented with an image and is asked to answer a set of pre-defined questions. The first question is to categorize the galaxy into one of three categories: smooth, features, or star/artefact. If a smooth morphology is chosen, the user is then asked to classify the shape into completely round, in between, or cigar-shaped. If on the other hand, the user classifies the galaxies as having features, then it should classify the galaxy as being clumpy or not. Usually, disk galaxies are classified as non-clumpy featured galaxies. At the end of the process, all users are asked if they find anything odd (e.g. rings, tails, asymmetries, mergers, disturbed galaxies) which can be used to identify irregular galaxies. The final results for each galaxy are given as the fraction of users that have answered each given possibility.

Appendix B: Mass dependence for the global sample

We explore in this appendix the global correlations of the studied parameters with stellar mass and local density. We show in Fig. B.1 the dependence of the parametric quantities studied in this manuscript as a function of stellar mass and environment for the global sample. For each parameter, we compute the Spearman correlation coefficient and the corresponding probability of the observed distribution being random for galaxies more massive than $10^{10}M_{\odot}$. We find that correlations between structural parameters and stellar mass are always stronger (less likely to be random) than that found for correlations with local density. We also find that the luminosity profile shape (traced by n and B/T) correlates more strongly with stellar mass and local density than the galaxy size does, the latter being roughly constant for varying stellar mass and local density.

In Fig. B.2 we show the dependence of the non-parametric quantities studied in this manuscript as a function of stellar mass and environment for the global sample. As is the case for the parametric quantities, we find that correlations between structural parameters and stellar mass are always stronger (less likely to be random) than that found for correlations with local density.

Appendix C: Environmental dependence for star-forming and quiescent galaxies

In this appendix, we explore, for the sake of completeness, the relations between the structural and morphological parameters with stellar mass and local density for the populations of star-forming and quiescent galaxies. In Figs. C.1 and C.2 we show the relations for parametric quantities of star-forming galaxies and quiescent galaxies, respectively. We show in Figs. C.3 and C.4 the relation for the non-parametric quantities of star-forming galaxies and quiescent galaxies, respectively. The overall conclusion from these plots is that the correlations with local density for all presented parameters are weak at best, and non-existent in others.

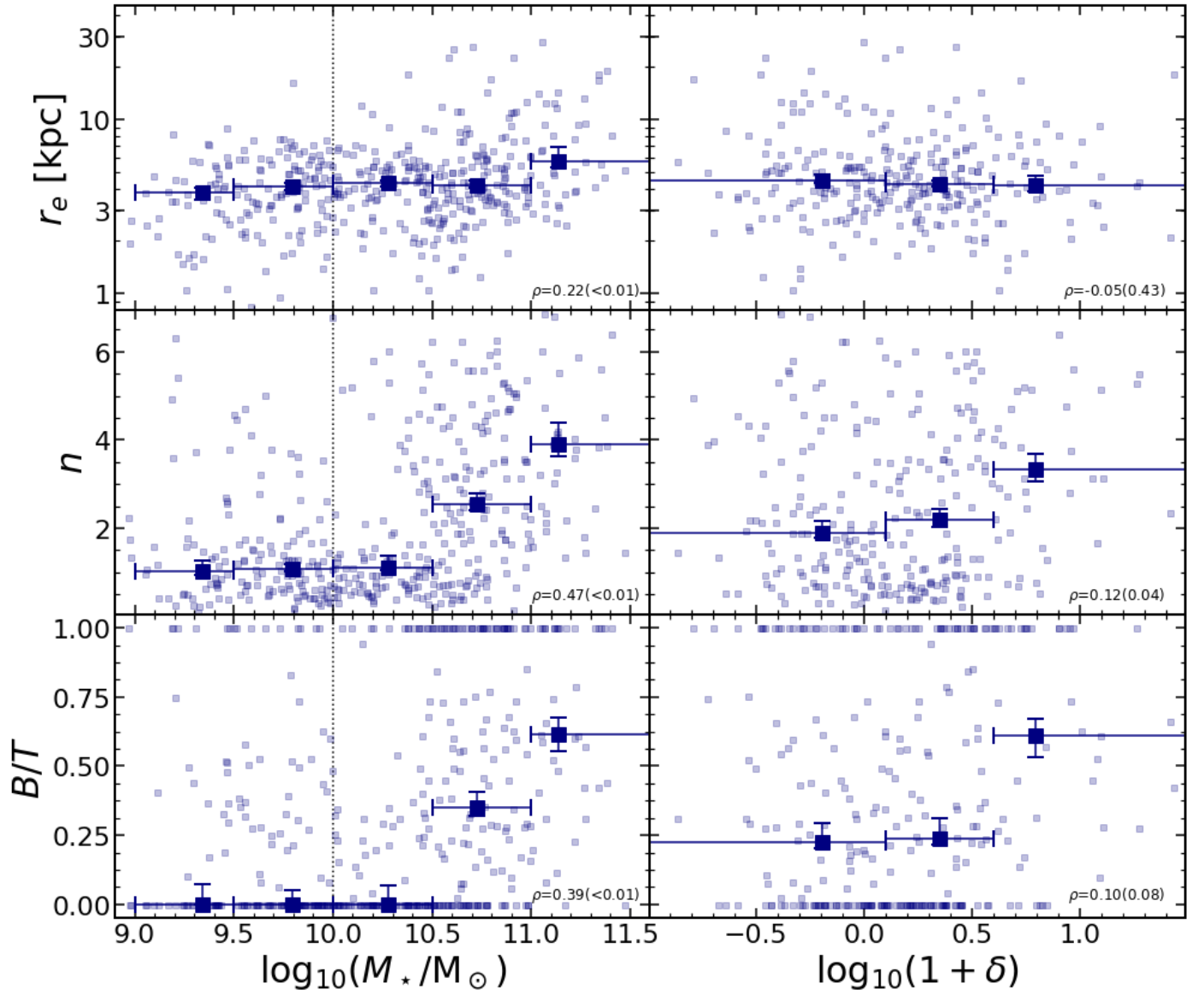


Fig. B.1. The dependence of $z \sim 0.84$ galaxy sizes (top), Sérsic indices (middle), and the bulge-to-total ratio (bottom) on the stellar mass (left) and the environment (right) for the global sample. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis (the coefficient is computed for galaxies with $M_{\star} > 10^{10} M_{\odot}$).

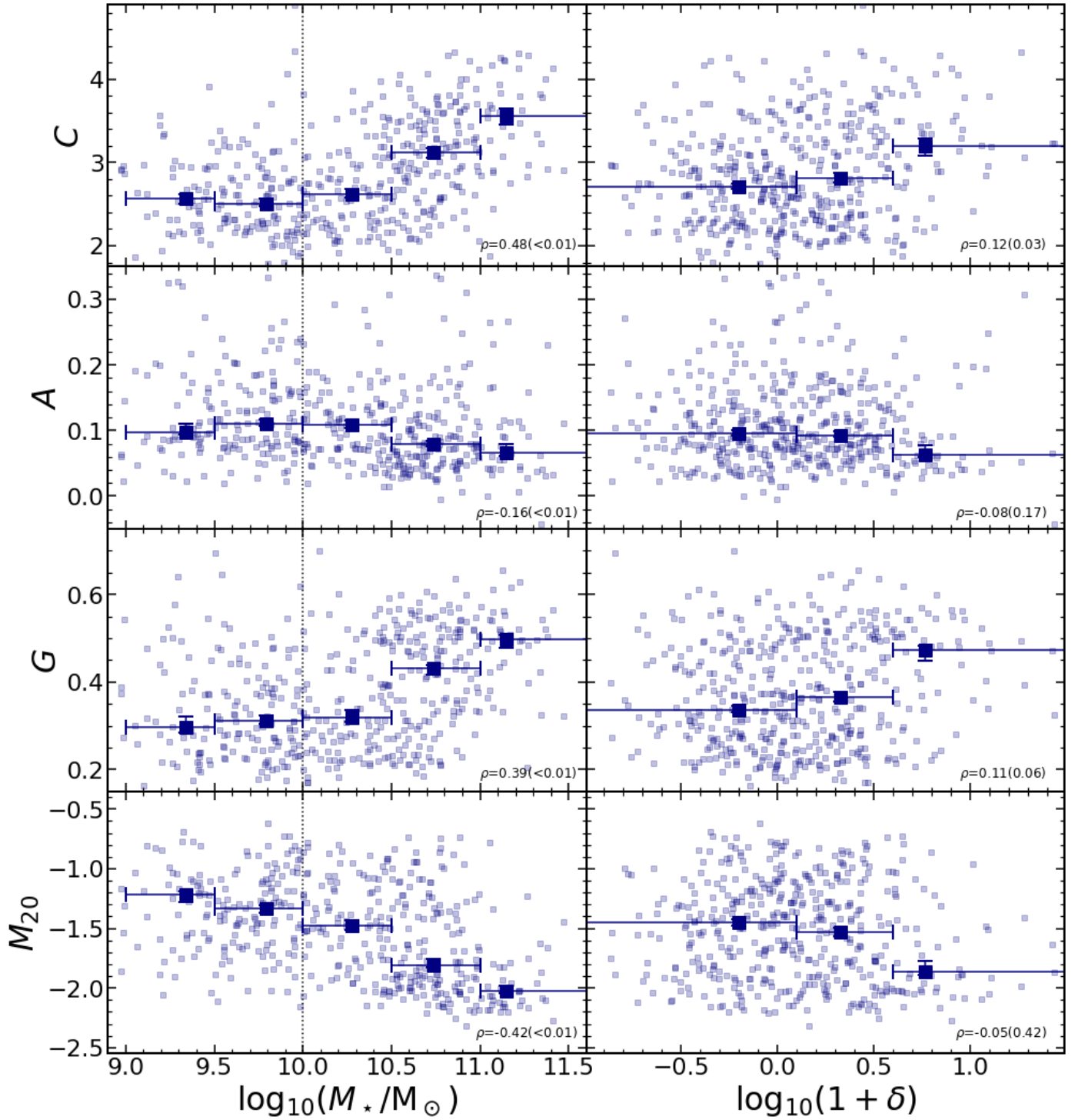


Fig. B.2. The dependence of non-parametric tracers (from top to bottom: light concentration, asymmetry, Gini, and moment of light) on the stellar mass (left) and the environment (right) for the global sample. In each panel, we show the Spearman correlation coefficient, ρ , and the corresponding probability of an uncorrelated dataset having the same distribution in parenthesis (the coefficient is computed for galaxies with $M_{\star} > 10^{10} M_{\odot}$).

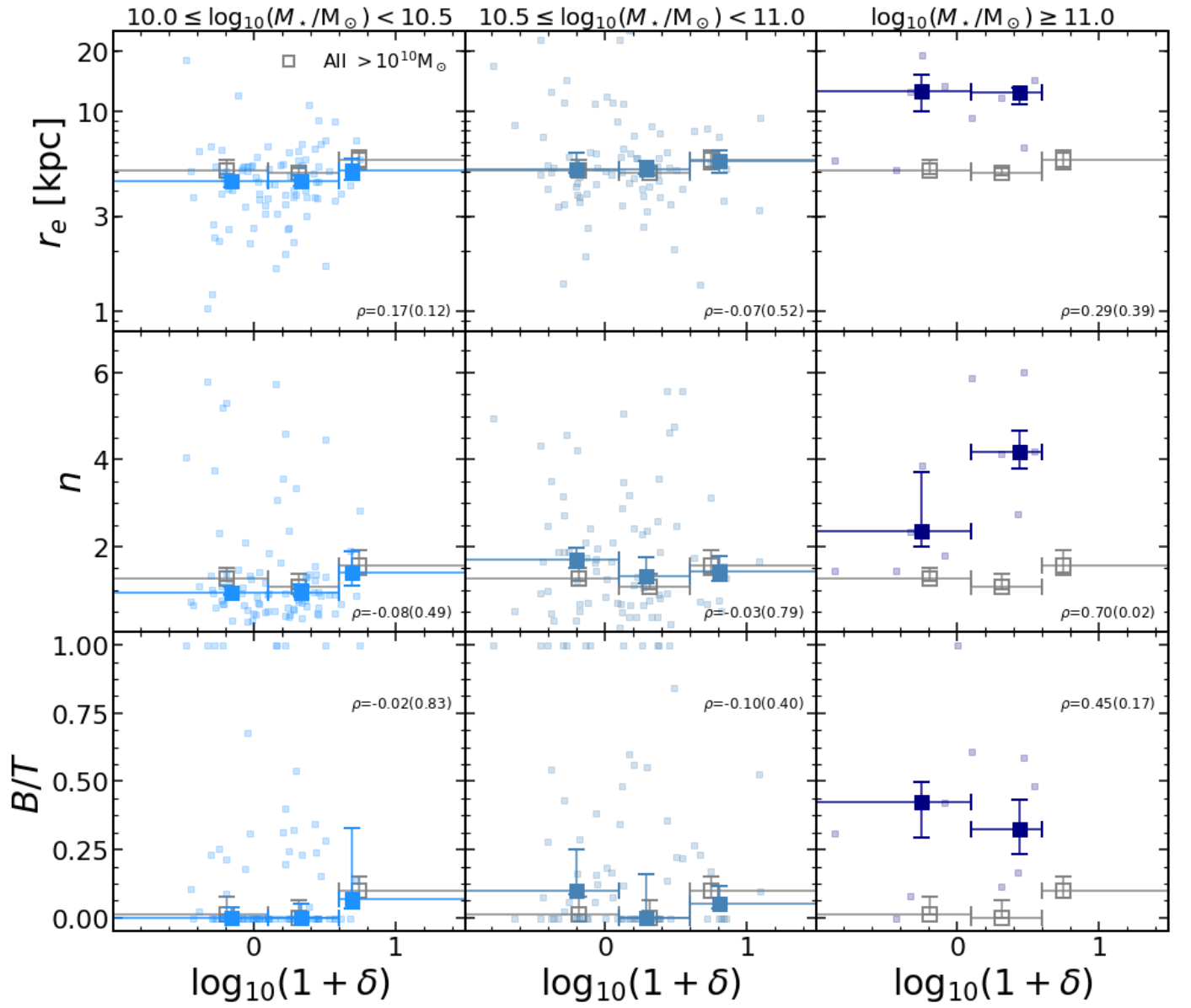


Fig. C.1. Same as Fig. 2, but considering only star-forming galaxies.

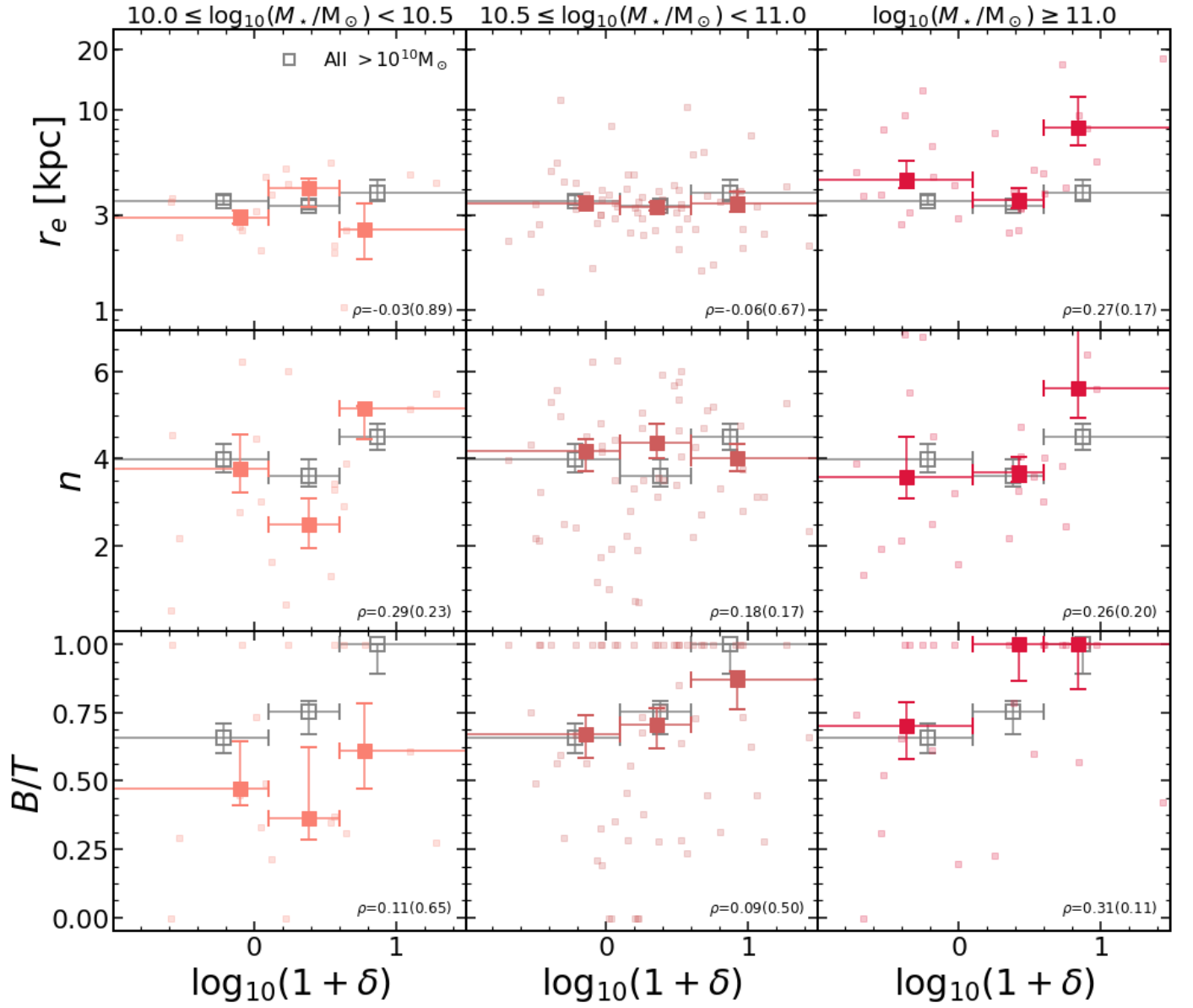


Fig. C.2. Same as Fig. 2, but considering only quiescent galaxies.

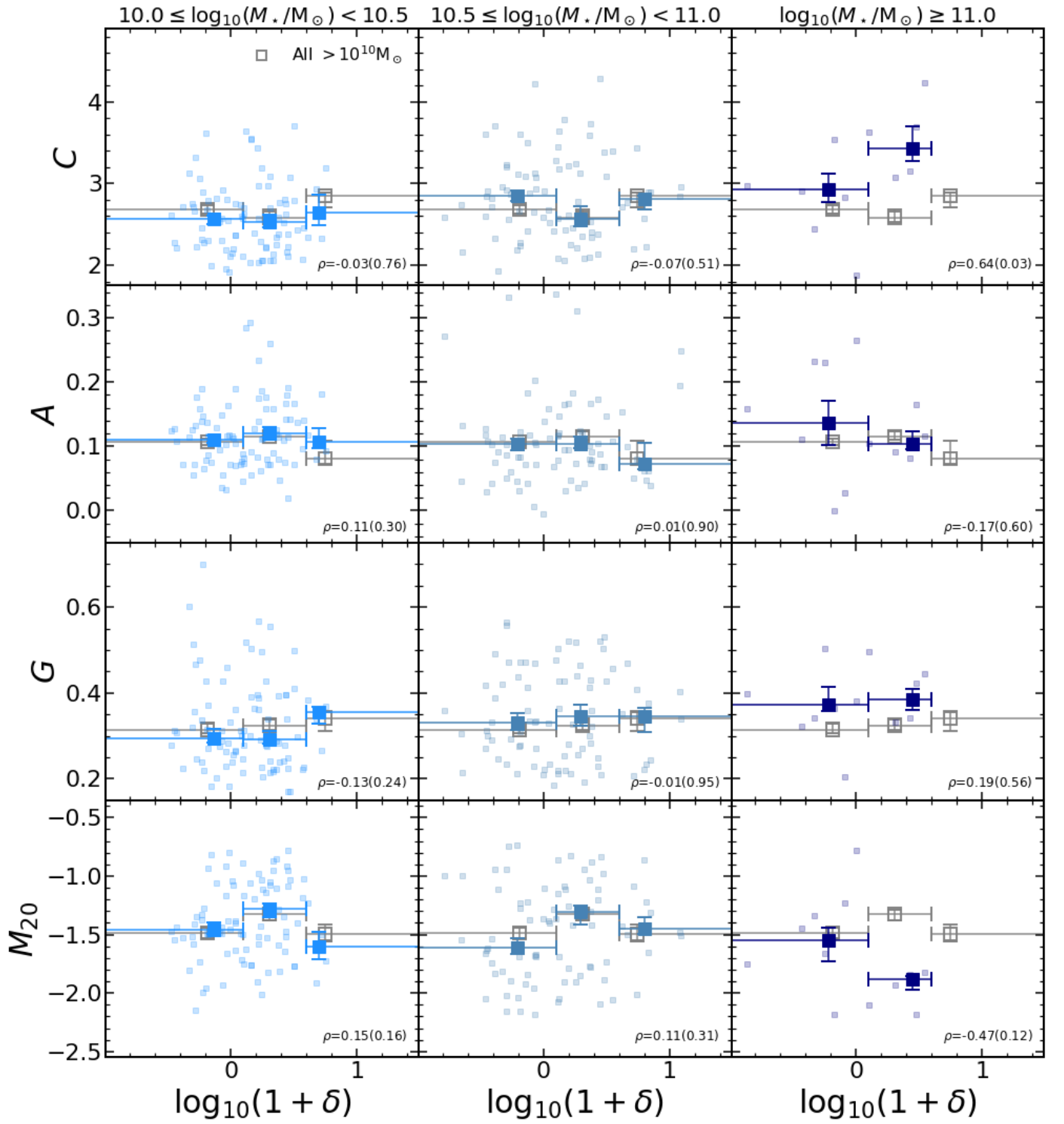


Fig. C.3. Same as Fig. 3, but considering only star-forming galaxies.

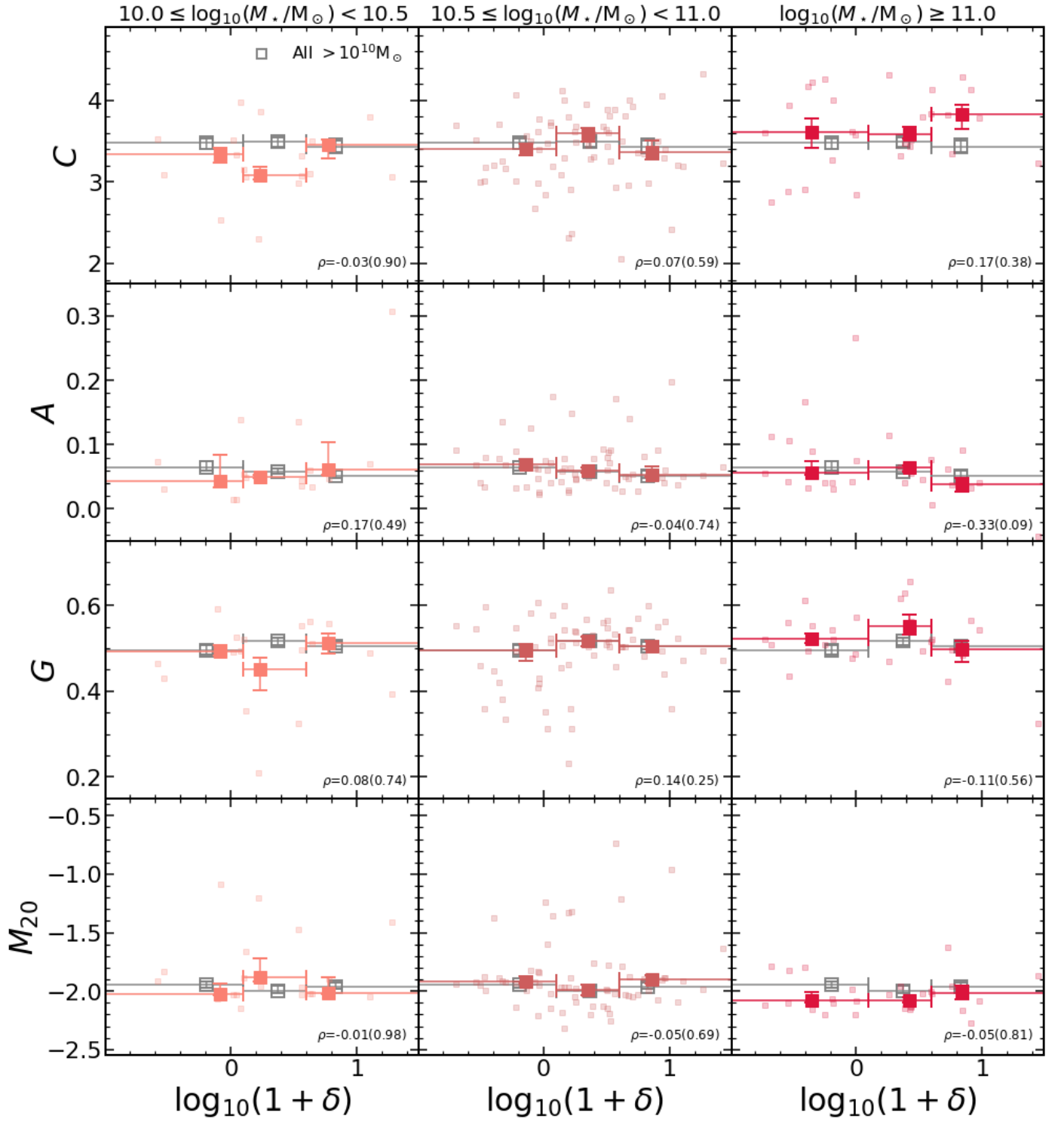


Fig. C.4. Same as Fig. 3, but considering only quiescent galaxies.